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SECOND EDITION

Tony Hunt's
Structures Notebook

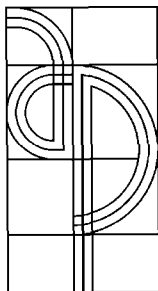


Tony Hunt's Structures Notebook

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Tony Hunt



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Preface to the First Edition

The *Structures Notebook* was originally written by Tony Hunt as a brief teaching aid for students at the Royal College of Art who had very little, if any, knowledge of physics or structural behaviour. The original *Notebook* was oversimplified but served its purpose as a primer. It has now been expanded into a more comprehensive book while retaining a simple visual and non-mathematical approach to structural behaviour.

The purpose of the *Structures Notebook* is to explain, in the simplest possible terms, about the structure of 'things', and to demonstrate the fact that everything you see and touch, live in and use, living and man-made, has a structure which is acted upon by natural forces and which reacts to these forces according to its form and material.

The book is divided into seven main sections, in a logical sequence, and is written in simple language. Each section, related to its text, contains a comprehensive set of hand-drawn sketches which show, as simply as possible, what the text is about. The book is almost totally non-mathematical, since the author believes very strongly that structural behaviour can be understood best by diagrams and simple descriptions and that mathematics for the majority of people interested in design is a barrier. The design of structures is a combination of art and science and to achieve the best solution, concept should always come before calculation.

Professor Tony Hunt

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Preface to the Second Edition

Since this book is about the basics of structure and structural behaviour, both of which are subject to the laws of physics and mathematics, it is difficult to know what to add.

This book was first published in 1997. The author feels that some key structural ideas and assemblies were not illustrated and they have now been included, together with some recent examples. These expand the range of ideas conceived by different designers and show further different ways of creating inventive structures and structural assemblies. These illustrations are included in a new Chapter 8.

Recently, with some designers, there has been a move away from orthogonal geometries to more random forms (see '*informal*' by Cecil Balmond). This has been aided by the enormous power of modern analytical and graphic computing, and has been driven by both architects' and engineers' interest in exploring more complex geometries. This adds to the complexity of design solutions and has to be considered as part of current design thinking.

Finally, the reading list has been added to for up-to-date references to books which I consider to be important for architects, engineers and designers.

Professor Tony Hunt

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1

Introduction

This book is about the basic structure of things. Its aim is to develop an understanding of essential structural principles and behaviour by a descriptive and largely non-mathematical approach. It relates to the structure occurring in such diverse objects as a bridge, a box for packaging, furniture, buildings etc. and it covers all the common structural elements singly and in composite form.

This book is a primer on the subject. There are a large number of books on building structures, the most important or relevant of which are listed in Appendix III.

2

Structure and structural form

Structure

What structure is

Structure is the load-carrying part of all natural and man-made forms. It is the part which enables them to stand under their own weight and under the worst conditions of externally applied force.

The designer

In the context of *structure*, a designer is one who conceives a structural part or a structural system which functions satisfactorily, is integrated successfully within the overall design and is appropriate for its purpose in terms of material and form.

The design process

Without a brief it is not possible to design, since there are no rules and no constraints. Therefore, no matter how sketchy, it is the brief which sets the basic framework for the designer. It provides the lead-in for the first analysis of the problem which then develops into an iterative process, with ideas being tested, modified, rejected, until an appropriate solution to the problem is reached.

Optimum design

A designer should generally aim for the optimum solution in order to obtain the maximum benefit with the minimum use of material within the constraints of strength, stiffness and stability. The result will be EFFICIENCY combined ideally with ELEGANCE AND ECONOMY.

Influences on the designer

The major influences on creative structural design are:

- Precedent* – what's gone on
- Awareness* – what's going on
- Practicality* – how to do it

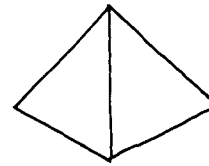
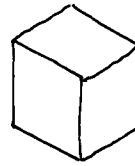
Structural form

Structures take one of four basic forms which may exist singly or in combination.

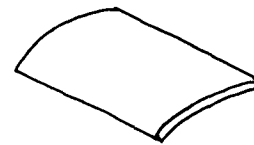
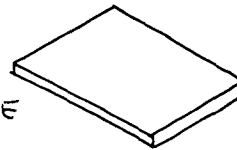
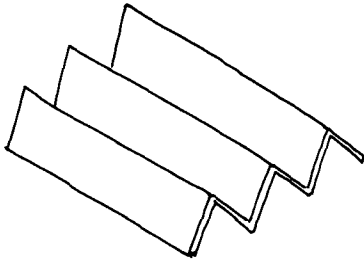
<i>Solid</i>	An homogeneous mass structure where the external surface is independent of the internal form – a three-dimensional solid body
<i>Surface</i>	An homogeneous surface where the external and internal forms are similar – a two-dimensional panel
<i>Skeletal</i>	A framework where the assembly of members gives a clear indication of the form usually using one-dimensional elements
<i>Membrane</i>	A flexible sheet material sometimes reinforced with linear tension elements used either as single cables or as a cable net. A variation is the pneumatic where air under pressure is contained by a tension membrane skin
<i>Hybrid</i>	A combination of two of the above forms of near equal dominance

For examples of all the above, see Chapter 7.

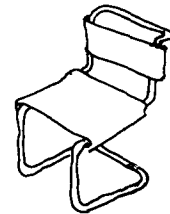
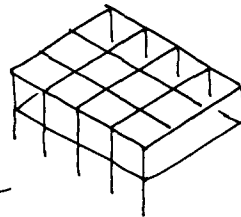
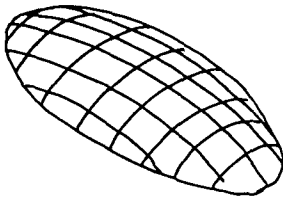
SOLID



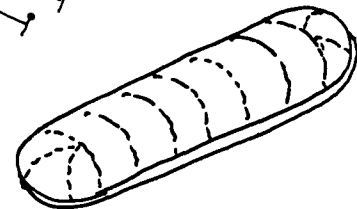
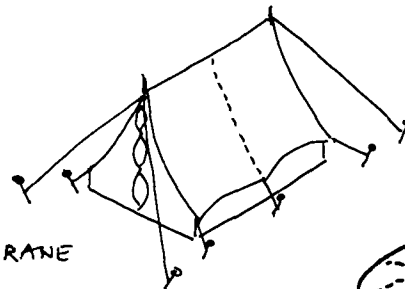
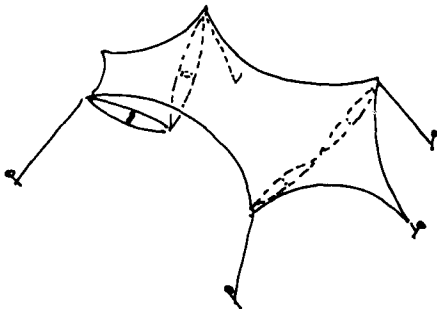
SURFACE



SKELETAL



MEMBRANE



Structural form in nature

Here are some examples of objects in nature, all of which have a structure in one or more forms:

Human and animal skeletons

Birds' wings

Fish

Flowers

Honeycombs

Leaves

Plants

Rock caves

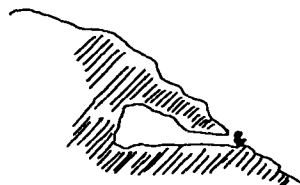
Shellfish

Snails

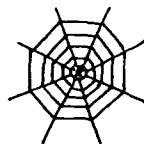
Snowflakes

Spiders' webs

Trees



CAVE



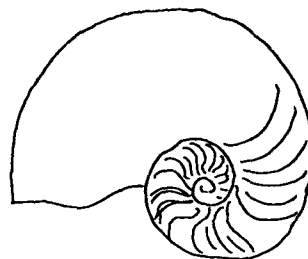
SPIDER WEB



FISH SPINE



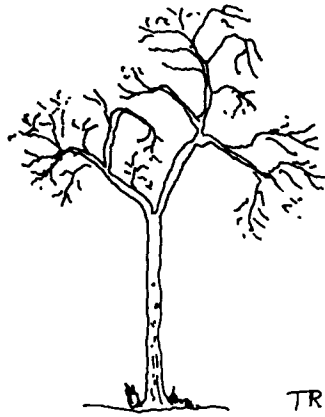
HONEY COMB



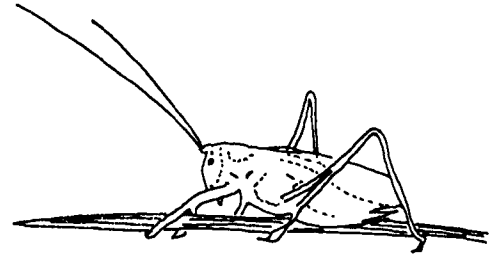
NAUTILUS



DAFFODIL



TREE



GRASS HOPPER

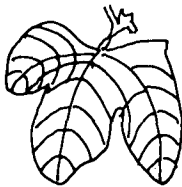
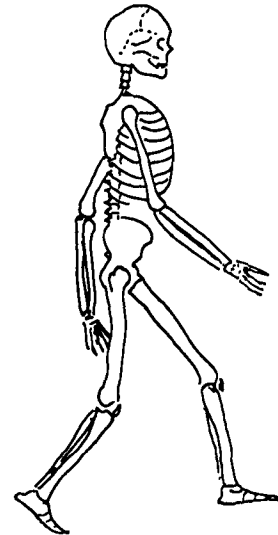


FIG LEAF



BIRD WING



SKELTON

Structural form – man-made

Here are some examples of man-made objects, all of which have a structure in one or more forms:

Aeroplanes

Bicycles

Bridges

Buildings

Cars

Clothes

Cranes

Dams

Engines

Fabrics

Fastenings

Furniture

Musical instruments

Packaging

Pottery

Roads

Sculpture (3-D art)

Ships and yachts

Sports gear

Technical instruments

Tents

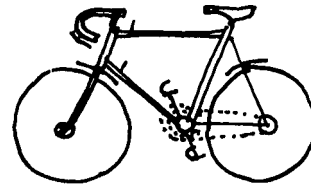
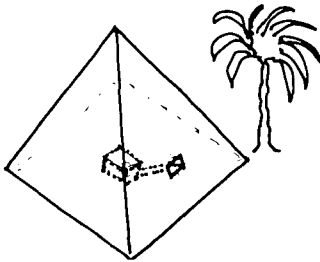
Tools

Toys

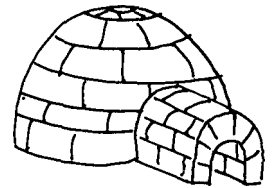
Tunnels

Wheels

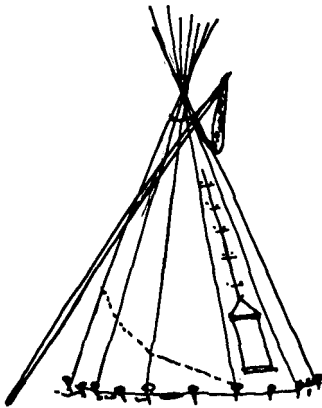
PYRAMID



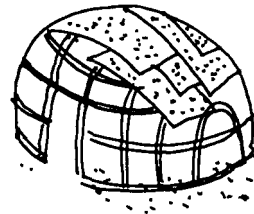
BKYLE



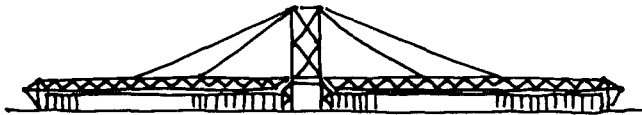
IGLOO



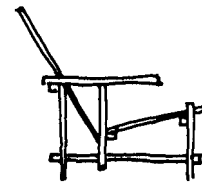
WIGWAM



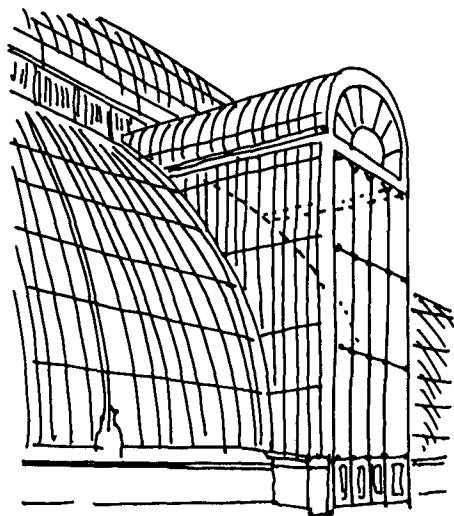
TWIG + BARK
HUT



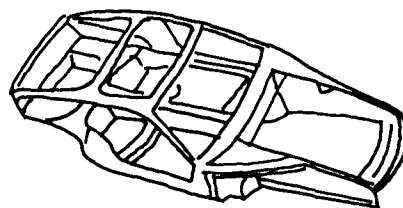
MICRO ELECTRONICS FACTORY



RIETVELD CHAIR

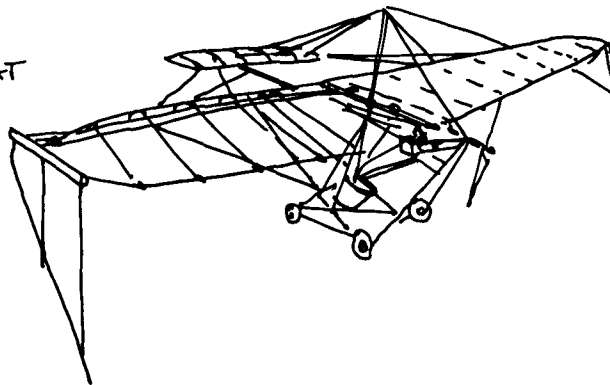


PALM HOUSE KEW

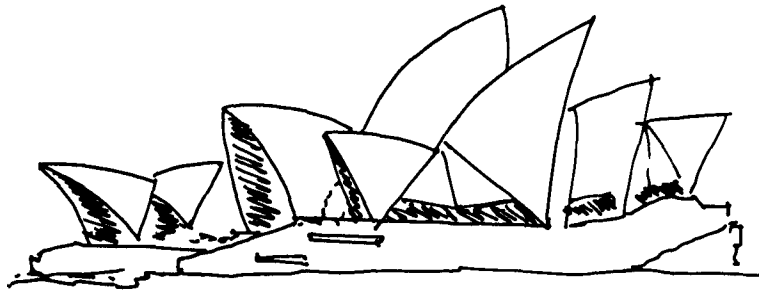


CAR BODY - MONOCOQUE

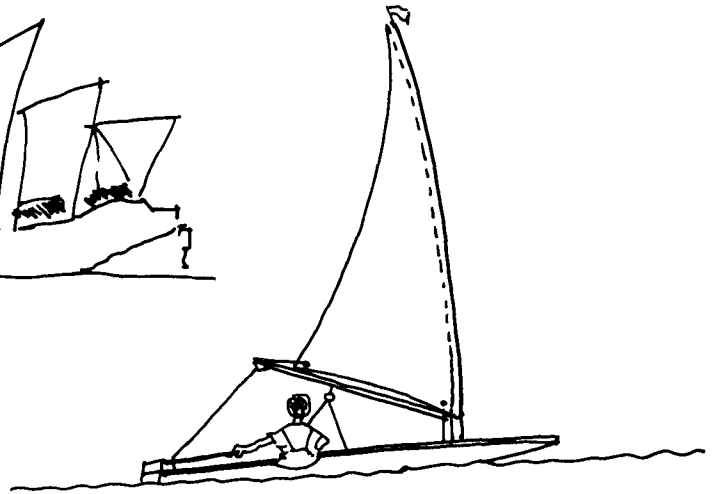
MICROLITE
SINGLE SEAT
AIRCRAFT



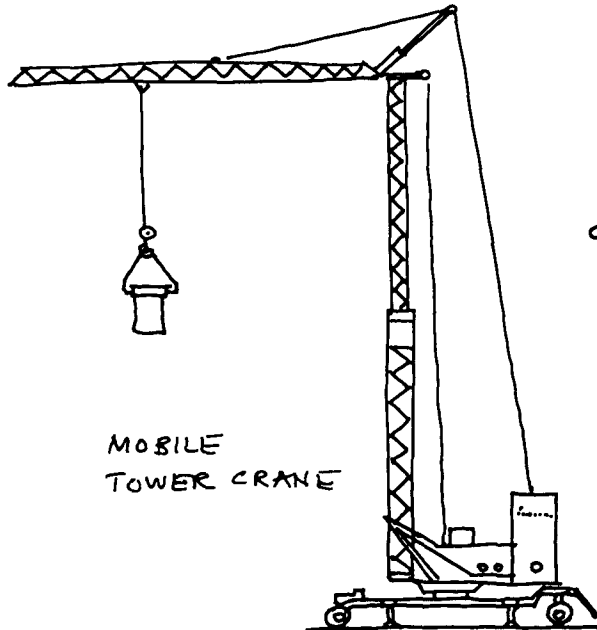
FORTH RAIL BRIDGE



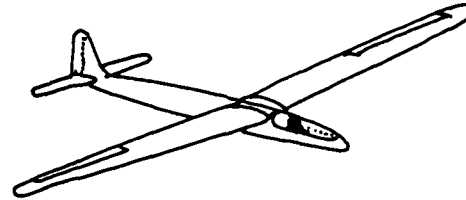
OPERA HOUSE



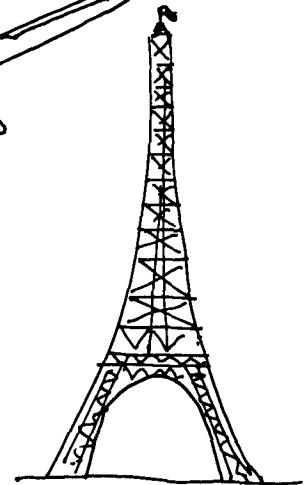
DINGHY



MOBILE
TOWER CRANE



SAILPLANE



EIFFEL TOWER

3

Structural materials

All materials have a stiffness and strength and are manufactured into a shape. Stiffness and strength are different, complementary characteristics and describe the properties of a solid material. Shape affects performance.

Strength

Strength is the measure of the force required to break the material.

A material can be strong or weak – see Appendix I.

<i>Mild steel</i>	stiff and strong
<i>Sheet glass</i>	stiff and weak
<i>Nylon rope</i>	flexible and strong
<i>Rubber</i>	flexible and weak

Stiffness

The majority of structural materials behave in an elastic manner according to Hooke's Law which states that elastic extension is proportional to load. When the load is removed, the material recovers its original length and shape.

Different materials have different stiffness characteristics. They can be: stiff, flexible, stretchy, springy or floppy.

This stiffness is defined for each material as the E -value – Young's modulus, named after its discoverer.

E is the value of stress/strain and is a constant for a given material.

Stiffness and strength do not necessarily go hand in hand as the above examples show.

Shape

Shape is the third property which affects the performance of a material in a particular loading situation. In pure tension, shape does not matter, but in all other loading modes – compression, bending and shear – the cross-sectional shape affects performance.

In general terms, for maximum performance, the material should be arranged in order to be as far away from the centre of the section as possible.

Material behaviour

Materials are either 'isotropic' or 'anisotropic' depending on their behaviour under load.

<i>Isotropic</i>	Providing equal performance in all directions in both tension and compression
<i>Anisotropic</i>	Providing differing performances in different directions and in compression and tension

Some examples:

Isotropic materials

Metals

Including steel, aluminium, bronze, titanium etc.

Anisotropic materials

Timber

Different values for compression and tension.
Different values for load parallel and perpendicular to the grain.

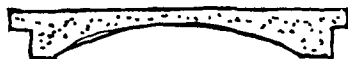
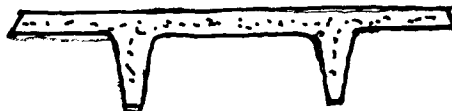
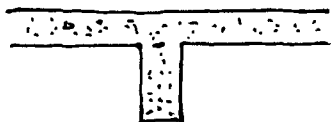
Concrete and masonry

Good in compression, poor in tension. Steel reinforcement provides the tension element in reinforced concrete.

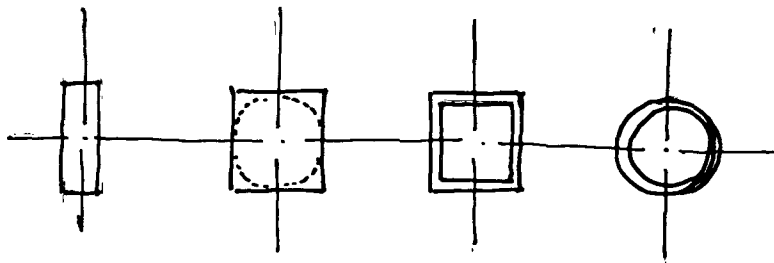
Plastics and reinforced plastics

Usually stronger in tension than compression.
A very wide range of performance according to type of plastic and reinforcement.

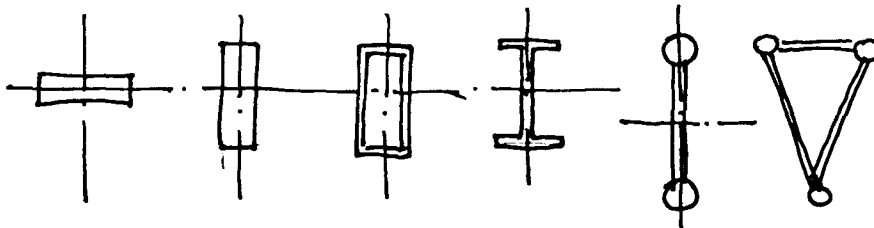
Concrete - insitu + pre cast



STRUTS



← LEAST GREATEST →
EFFICIENCY



BEAMS

COMMON STRUCTURAL MATERIAL SHAPES

Hot rolled steel

Extruded Aluminium



Note - Aluminium can be extruded through most die shapes

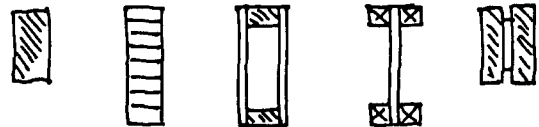
Cold formed steel



Cables/rods



Timber



Masonry - cut to squared stones
or pressed + baked as bricks

Concrete - cast to shape in
formwork moulds

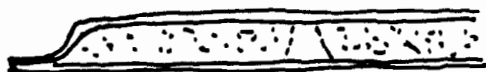
COMPOSITE MATERIAL PANELS



Aluminium skins +
rigid plastics foam core

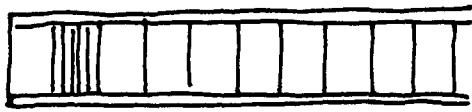


Aluminium skins + phenolic resin
coated paper core (Nomex)



↑stiffener as required

Injection moulded GRP
with rigid isocyanate core



GRP skins on end-grain
Balsa core



Vacuum-formed super plastic
aluminium with rigid foam core



ETPE foil in aluminium frame
Air-inflated

4

Loads on structure

All structures develop internal forces which are the result of external applied loads and the weight of the structure itself.

Loads are conventionally divided into a number of classifications under the following headings:

Permanent

Dead load The self-load of the object or part due to its mass

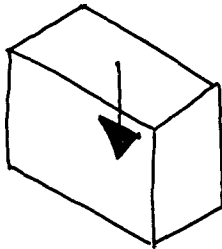
Temporary

Imposed load The 'user' load which is removable and thus is a 'live' load

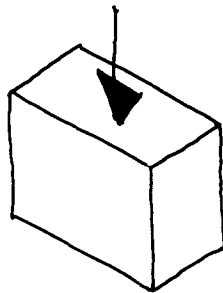
Thermal load The load induced by temperature change causing expansion or contraction of the object

Dynamic load A cyclical load caused by varying external conditions which cause the object to vibrate or oscillate

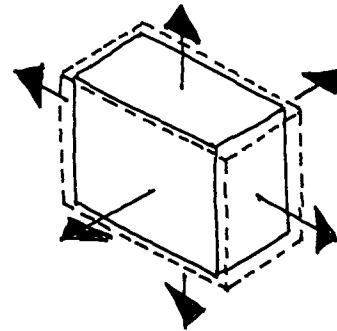
Structures must always be designed for the worst anticipated combination of loading otherwise unserviceability or failure can result.



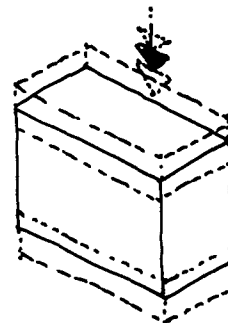
DEAD LOAD



IMPOSED LOAD



THERMAL LOAD



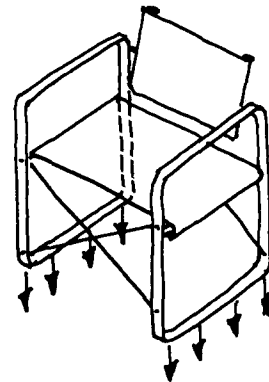
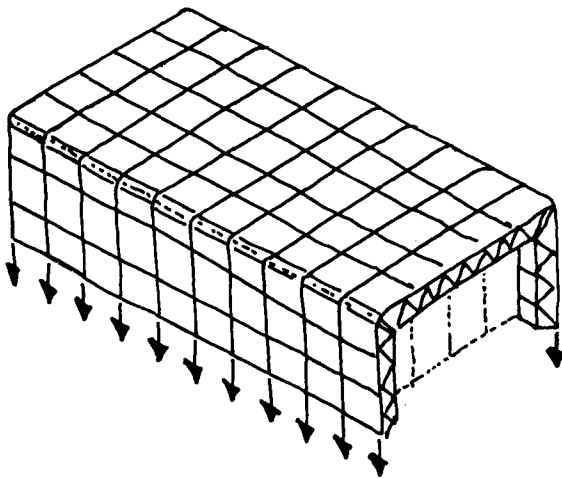
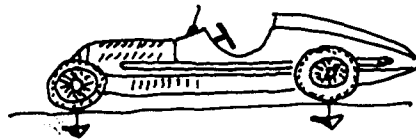
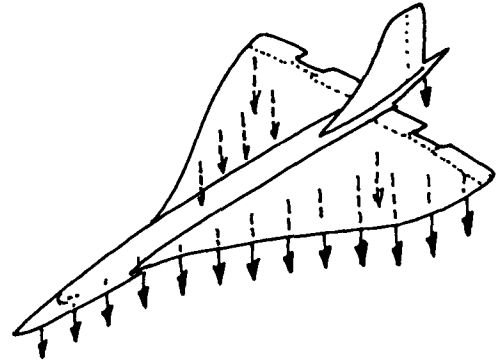
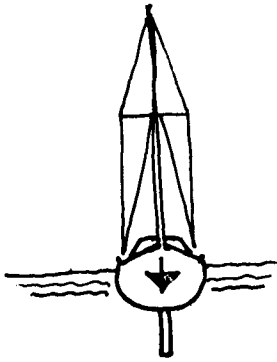
DYNAMIC LOAD
ON/OFF

Examples of load cases

Dead load

<i>Aeroplane</i>	The weight of the plane without fuel, passengers or baggage
<i>Building</i>	The weight of the structure, cladding, fixed equipment etc.
<i>Vehicle (bus, railway carriage, truck, passenger car)</i>	The weight of the vehicle without fuel, passengers or freight
<i>Yacht</i>	The unladen weight of the vessel
<i>Object (e.g. chair)</i>	The weight of the chair itself

All these are examples of permanent load.



Imposed load

Aeroplane

The fuel, passengers and cargo all of which are variable

Building

The 'user' load – people, furniture, factory machinery, any equipment which is movable. Environmental loads – snow, the 'static' effects of wind

Vehicle

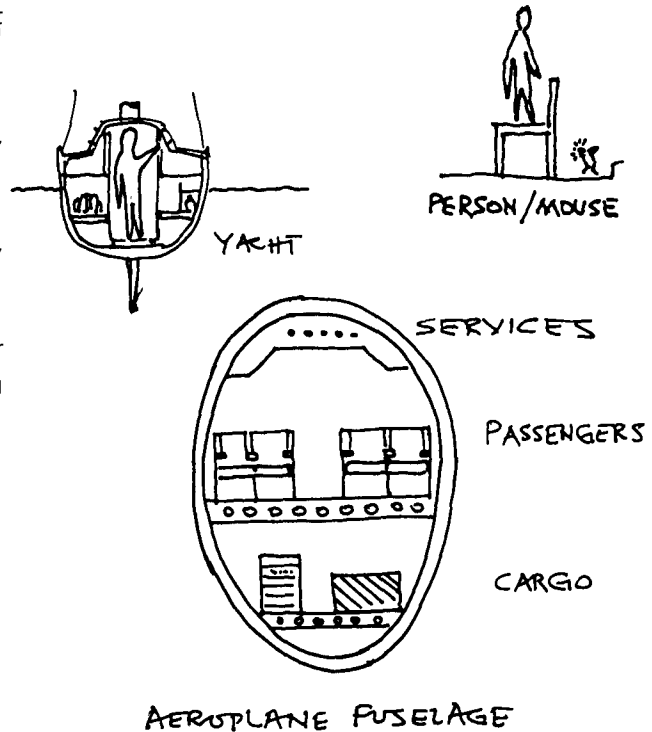
The fuel, passengers, freight etc.

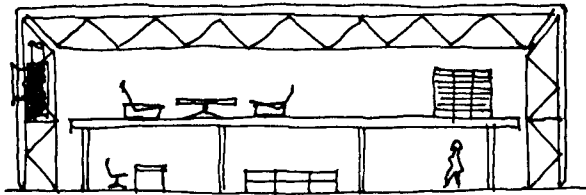
Yacht

The crew, stores, fuel, water etc.

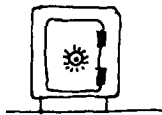
Object (chair)

A person sitting or standing on or tilting a chair





USER LOADS



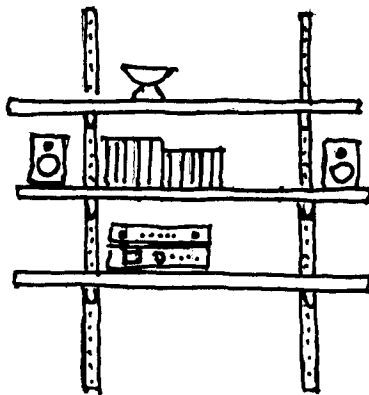
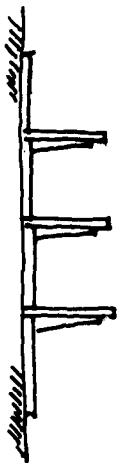
SAFE



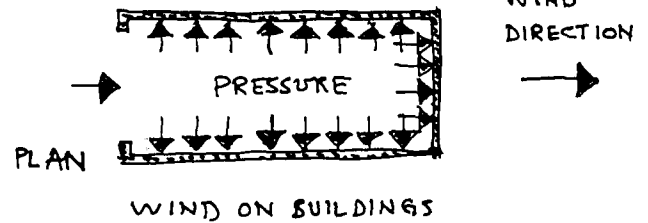
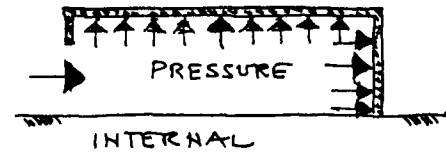
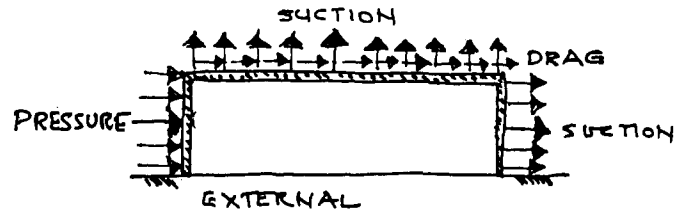
CABINET



MACHINERY

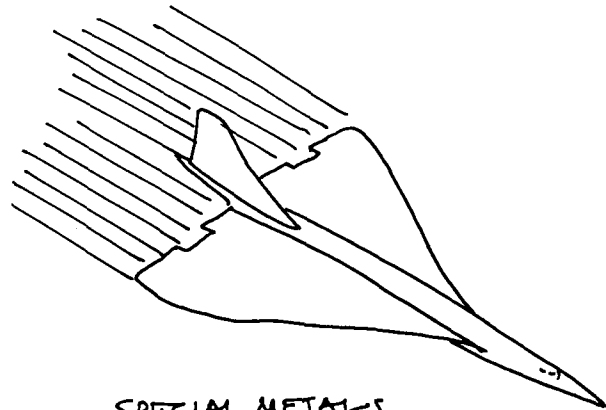
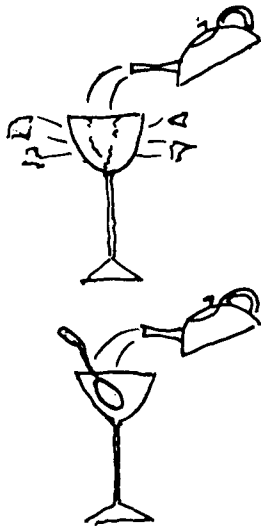


SHELF UNIT

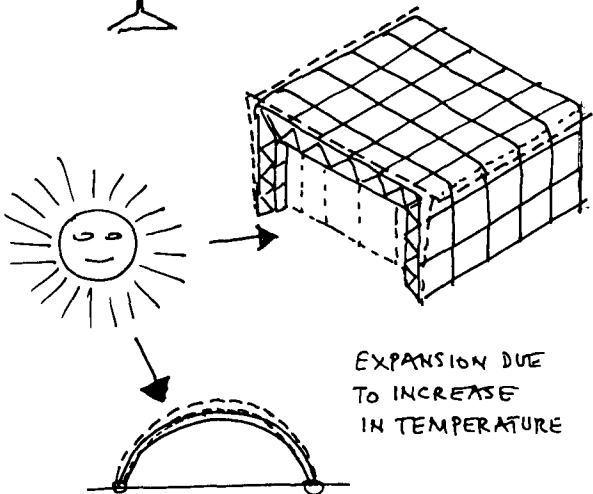


Thermal load

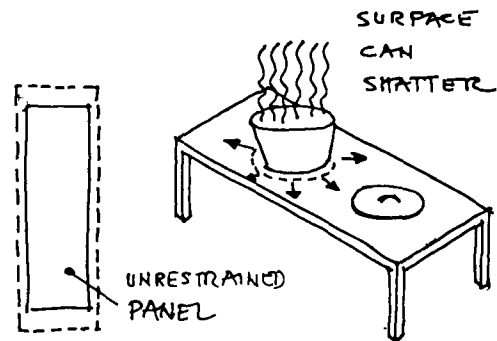
<i>Aeroplane</i>	Temperature changes in the skin due to height and speed (speed causes air friction and generates heat)
<i>Building</i>	Roofs and walls facing the sun are subject to diurnal temperature change. Elements may have a different outside and inside temperature
<i>Vehicle</i>	The engine increases in temperature due to combustion and outside air temperature. It requires cooling
<i>Object</i>	A hot liquid poured into a glass can cause it to shatter – thermal shock. A spoon in the glass acts as a 'heat sink'



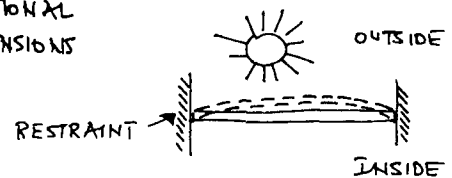
SPECIAL METALS
ARE REQUIRED TO
RESIST HIGH TEMPERATURES



EXPANSION DUE
TO INCREASE
IN TEMPERATURE



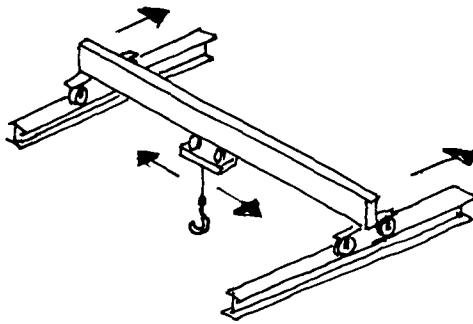
EXPANSION
PROPORTIONAL
TO DIMENSIONS



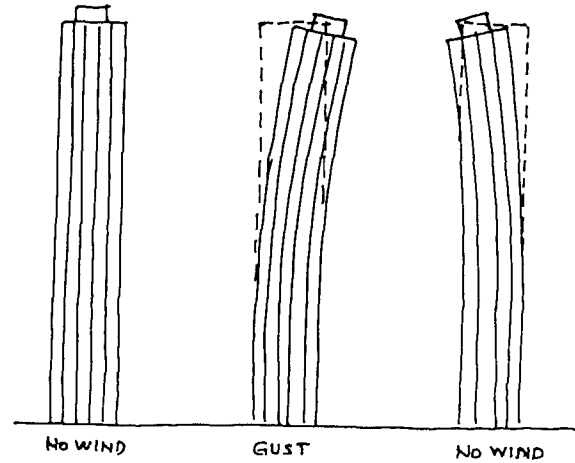
Dynamic load

<i>Aeroplane</i>	A sudden change in direction causes dynamic flexing of the wings and G forces on humans
<i>Building</i>	Gusty wind conditions cause oscillations. Surge caused by a lift starting and stopping. Surge due to overhead crane travel
<i>Vehicle</i>	Accelerating, decelerating and cornering all cause dynamic loads on parts of the vehicle
<i>Yacht</i>	Wind on the sail causing heel (overturning). 'Pounding' of the hull in heavy seas
<i>Bridge</i>	Rolling loads cause the bridge deck to flex
<i>Object</i>	Rocking or tilting a chair is dynamic and affects the joints

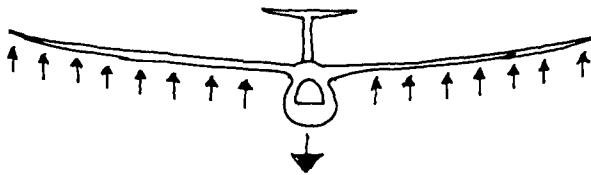
Imposed, thermal and dynamic loads are all temporary loads but their worst combination added to the dead load must be considered for design purposes.



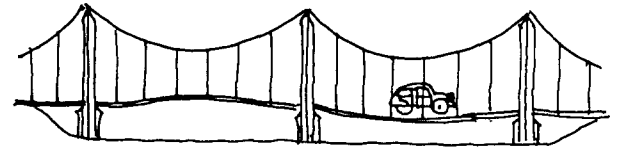
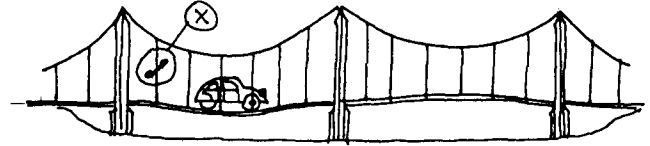
OVERHEAD TRAVELLING CRANE
- CREATES SURGE



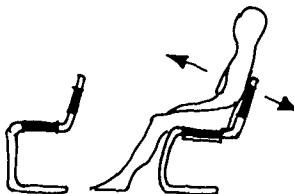
WIND INDUCED OSCILLATION ON A TOWER



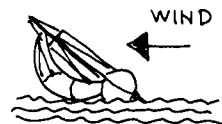
DROP INTO AIR POCKET CAUSES EXTRA LOAD
- WINGS FLEX



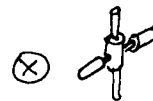
DYNAMIC LOADING CAUSES
FLEXING OF CABLES AND BRIDGE DECK



CHAIR FLEXES



YACHT HEELS



SHOCK BRIDGE DAMPER

5

Equilibrium

To stand up and stay in place structures must be in equilibrium.

External loads act on a structure and induce internal forces, both loads and forces having magnitude and direction.

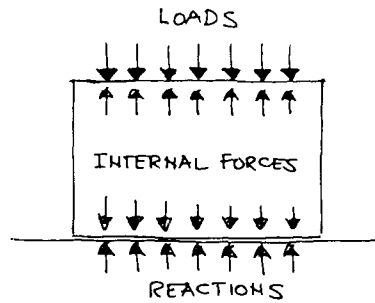
For equilibrium, reactions must act in an equal and opposite sense to the applied loads.

There are three conditions which may have to be satisfied to achieve equilibrium depending on the form of loading. These conditions are expressed as simple equations with meanings as follows:

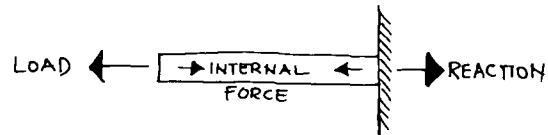
- $V = 0$ The sum of vertical loads and reactions must equal zero
- $H = 0$ The sum of horizontal loads and reactions must equal zero
- $M = 0$ Clockwise moments must equal anti-clockwise moments
Moment = load $\times$ distance of load from support or point of rotation

- P = Load (linear)
- R = Reaction (linear)
- M = Moment (bending or rotation)
- Σ = Sum

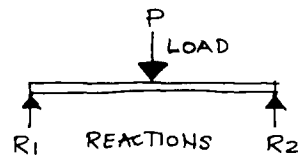
$$V = 0$$



$$H = 0$$

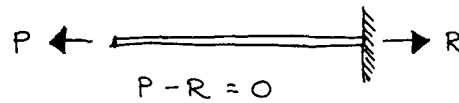


$$V = 0$$



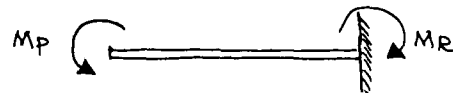
$$P - (R_1 + R_2) = 0$$

$$H = 0$$



$$P - R = 0$$

$$M = 0$$



$$M_P - M_R = 0$$

Examples of equilibrium

Vertical The load and reactions of an object sitting on the floor
A horizontal structure carrying a vertical load producing end reactions

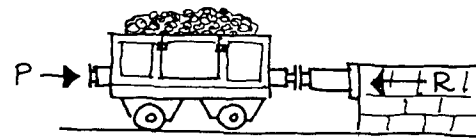
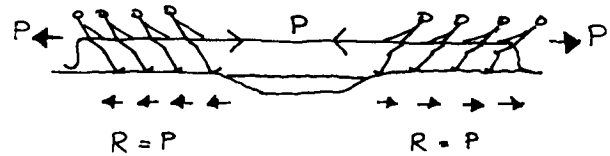
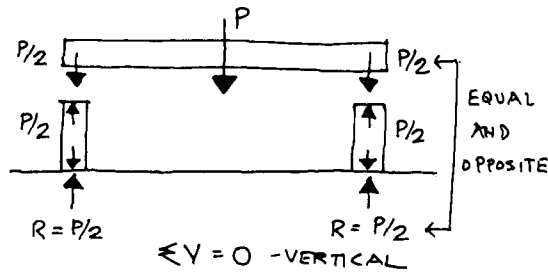
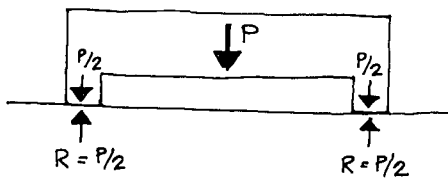
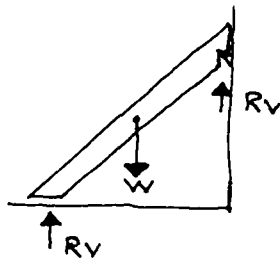
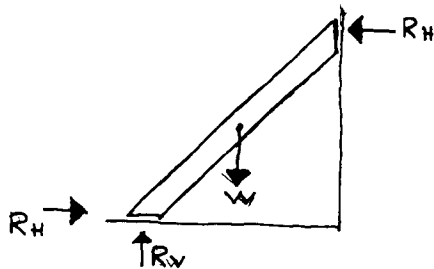
Horizontal The tug of war where, for equilibrium, both teams must pull with equal force.
The vehicle travelling horizontally which meets an obstruction

Rotational The see-saw where the sums of the loads x their distance from the point of support must equal for balance

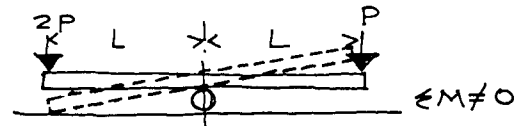
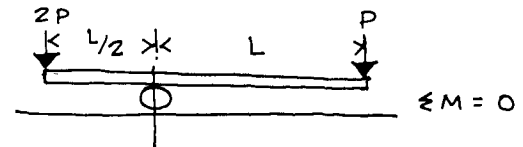
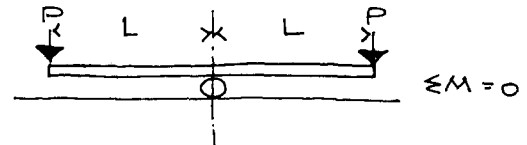
Notes:

Σ = sum

$\neq$ = not equal



$\Sigma H = 0$ - HORIZONTAL



ROTATION

$\Sigma = \text{SUM} \quad \neq = \text{NOT EQUAL}$

Equilibrium

W is constant for object

As P increases, rotation increases

When action line of W falls outside base then object is unstable and falls over

For stability

$$P_y < W_x$$

If y increases and x decreases, instability occurs when $P_y > W_x$

Graphical solution

P and W are drawn to scale to represent load magnitude and direction, R is resultant

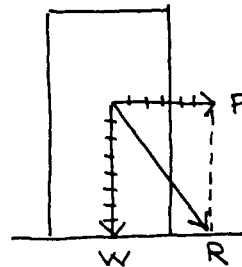
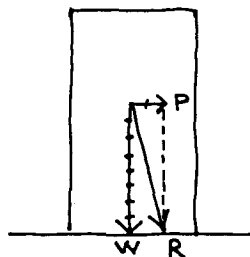
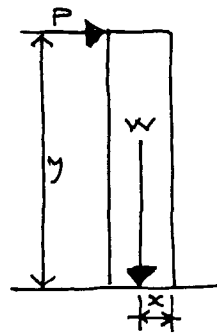
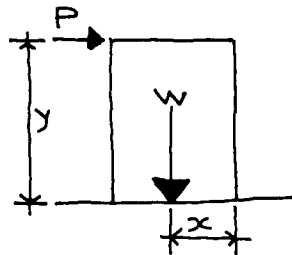
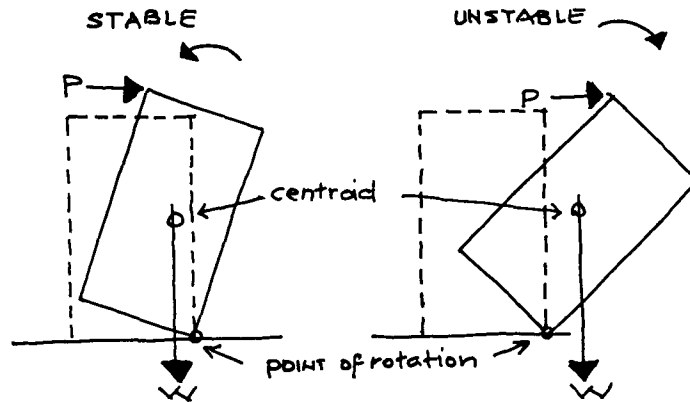
P = external load

W = weight of object

R = reaction

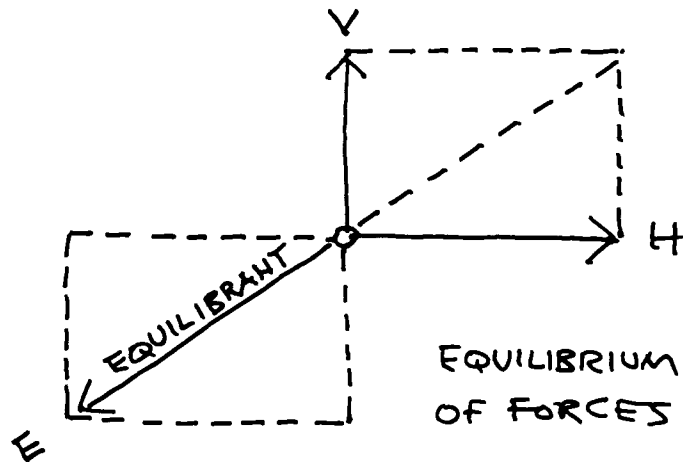
$>$ greater than

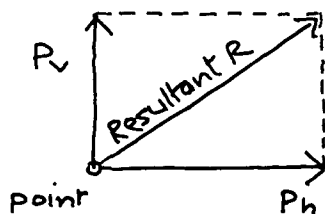
$<$ less than



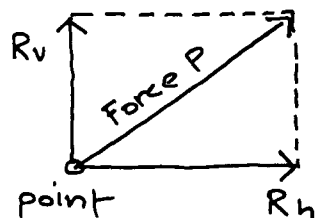
Parallelogram of forces (vectors)

Forces acting at a point in a direction other than vertical or horizontal can be resolved into vertical and horizontal by a vector *diagram* drawn to scale or by trigonometry. Similarly, two forces can be resolved into a resultant by the same method. The opposite of the resultant forms the equilibrium force.



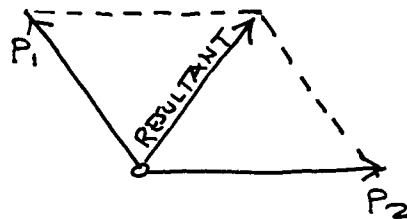
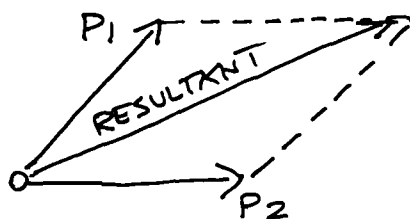


2 Forces at Rt. angles
1 Resultant



1 Force
2 Resultants at Rt. angles

TRIANGLE OF FORCES



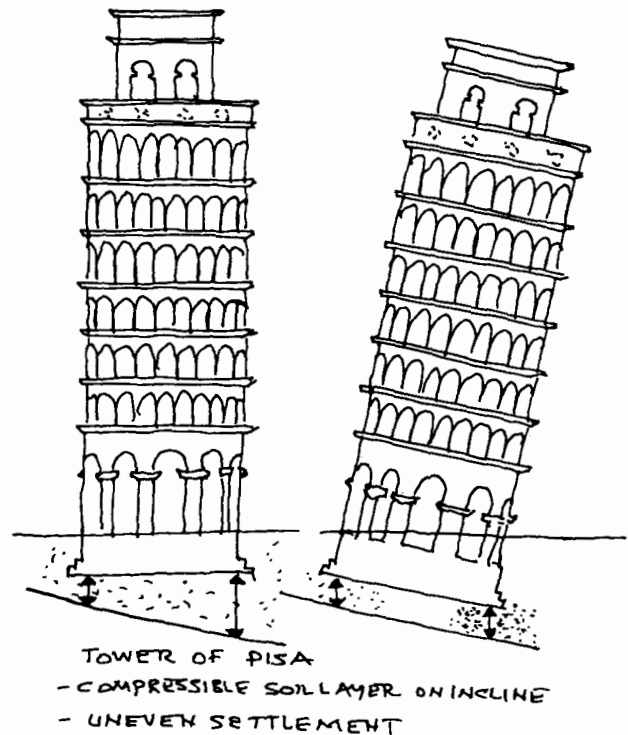
PARALLELOGRAM OF FORCES

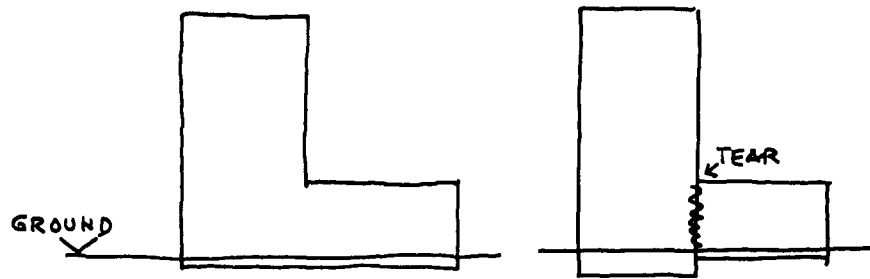
Settlement and earthquake behaviour

Both settlement and earthquakes can cause movements and distress in building structures.

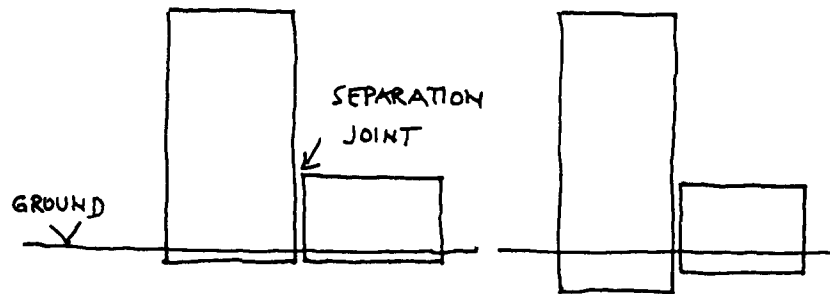
Settlement occurs due to compression of the soil under the foundations. Differential settlement occurs due to uneven bearing capacity of the soil or to uneven loading.

Earthquakes give rise to horizontal ground movement and can also be the cause of settlement due to ground compaction.

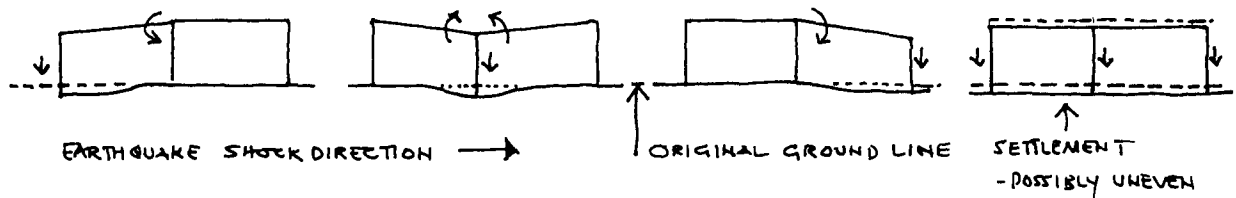




UNEVEN LOADING - DIFFERENTIAL SETTLEMENT
AND DAMAGE



UNEVEN LOADING - DIFFERENTIAL SETTLEMENT
NO DAMAGE



EARTHQUAKE BEHAVIOUR - SINGLE STOREY FRAME BUILDING

6

Structural elements and element behaviour

Structural elements

The design of a structural element is based on the loads to be carried, the material used and the form or shape chosen for the element. See Chapter 7.

The elements from which a structure is made or assembled have, in engineering or building terms, specific names which are used for convenience. In other disciplines such as naval architecture and furniture design the names are different but the functions are the same.

The elements

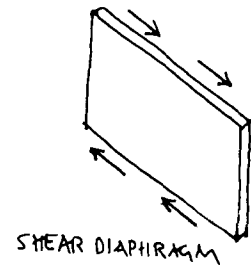
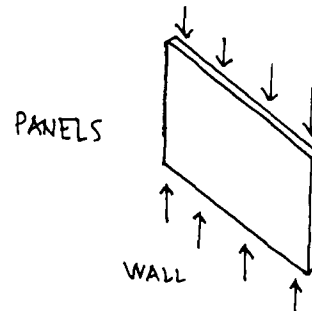
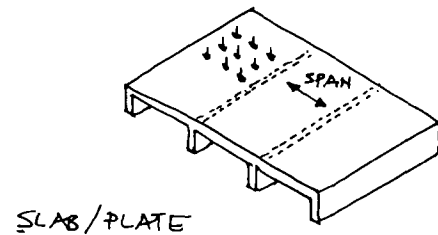
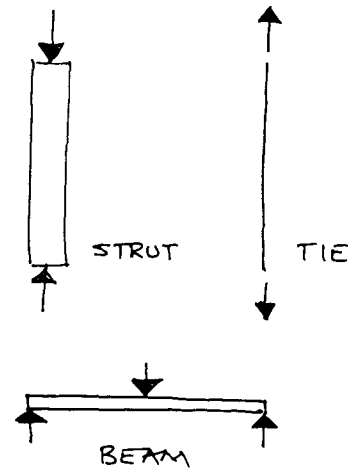
<i>Strut</i>	A slender element designed to carry load parallel to its long axis. The load produces compression
--------------	---

Tie A slender element designed to carry load parallel to its long axis. The load produces tension

Beam Generally a horizontal element designed to carry vertical load using its bending resistance

Slab/plate A wide horizontal element designed to carry vertical load in bending usually supported by beams

Panel A deep vertical element designed to carry vertical or horizontal load



Element behaviour – deformation

The loaded behaviour of structural elements is dependent on internal and external factors.

Internal factors – type of material, cross-sectional shape, length, type of end fixity

External factors – type of position and magnitude of load

Under load, elements deform in the following ways:

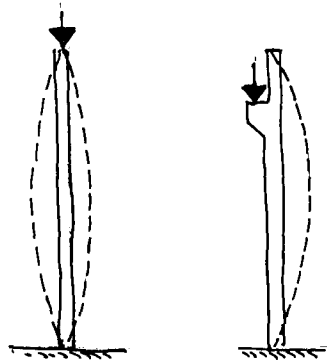
Struts compress under load and can buckle if not stabilized laterally

Ties extend under load

Beams and slabs deflect due to bending

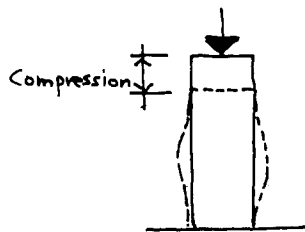
Panels deform due to in-plane load

Concentric Load Eccentric Load



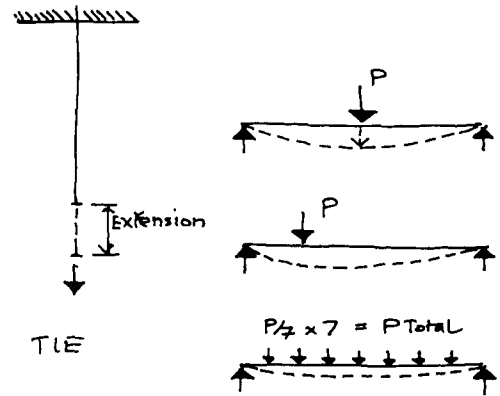
BUCKLING

Either way One way

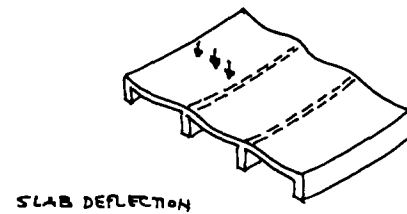


SHORTENING

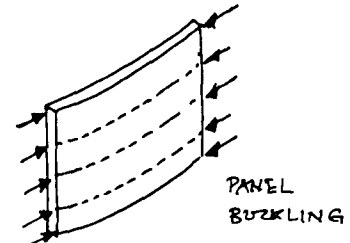
STRUTS



BEAM



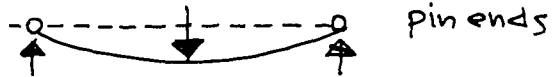
SLAB DEFLECTION



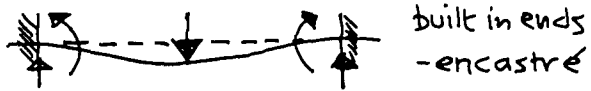
PANEL
BUCKLING

DEFORMATION UNDER LOAD

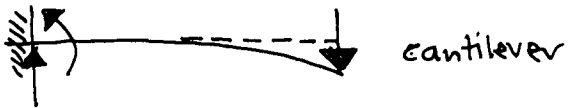
BEAMS



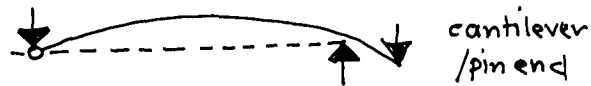
pin ends



built in ends
- encasté



cantilever



cantilever
/ pin end

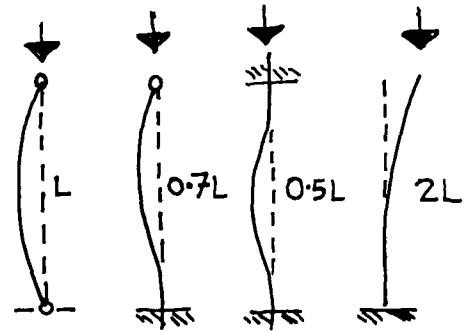


Propped
cantilever



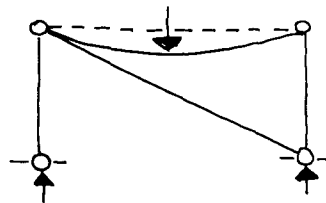
continuous 2-span beam

COLUMNS

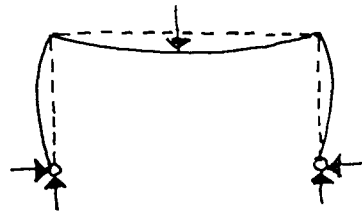


Effective Length / End Fixity

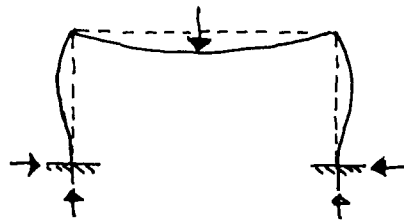
FRAMES



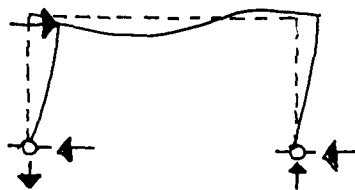
4 Pins + 1 strut



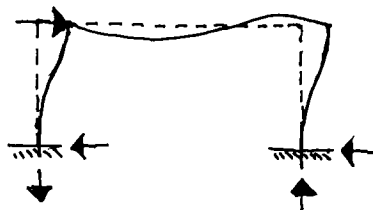
2 Pins
2 Stiff joints



4 Stiff joints



2 Pins
2 Stiff joints

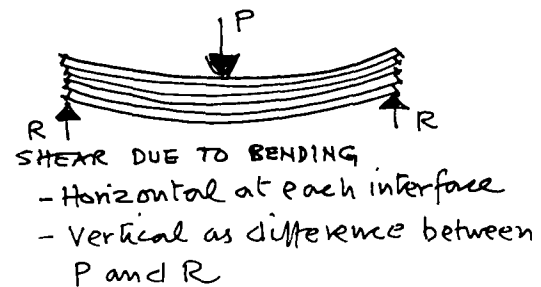
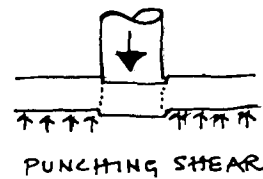
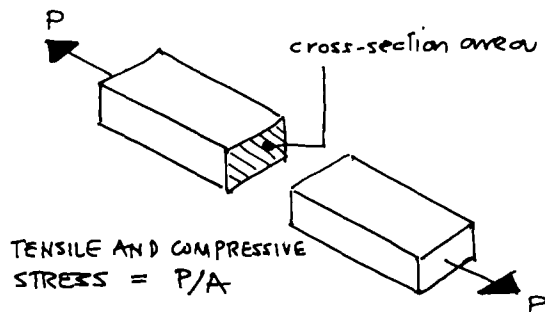
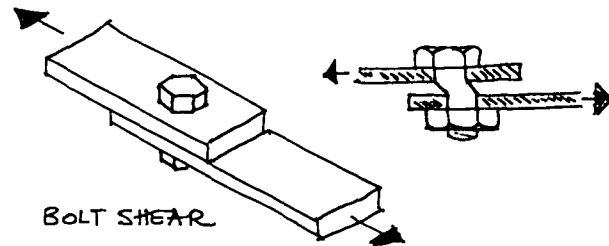
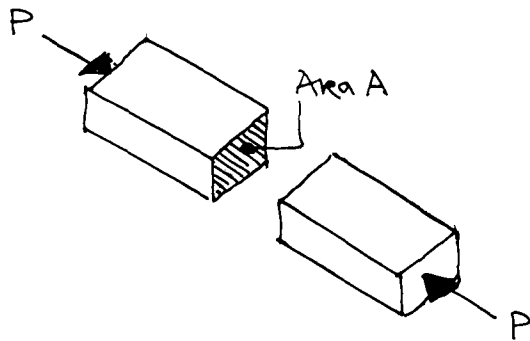
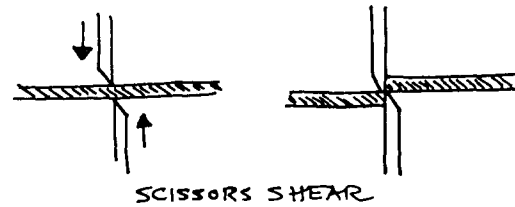
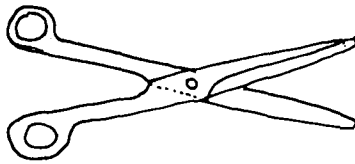


4 Stiff joints

Element behaviour – stress

When an element is loaded it becomes stressed. The type of stress and its effects on an element are as follows:

<i>Tensile</i>	The particles of material are pulled apart and the element increases in length. A tie is in tension
<i>Compressive</i>	The particles of material are pushed together with a consequent decrease in length. A strut is in compression
<i>Shear</i>	The particles of material slide relative to one another
<i>Torsion</i>	A form of shear caused by twisting
<i>Bending</i>	A combination of tension, compression and shear. Beams are in bending



Some stress and strain definitions

Stress $f = \text{load per unit area} = P/A$

Ultimate stress $f_u = \text{the stress at which a material fails}$

Working stress $f_w = \text{the safe maximum stress for a material}$

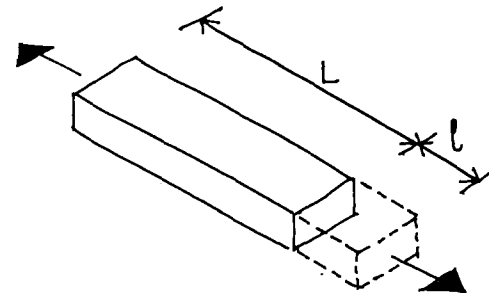
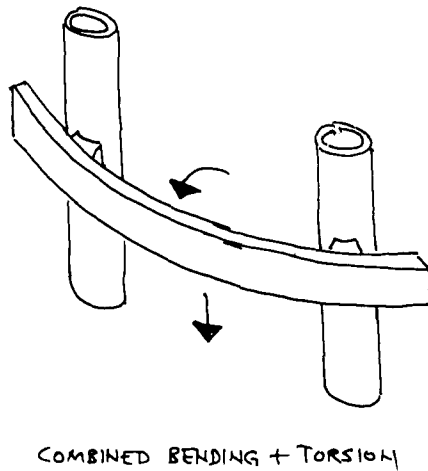
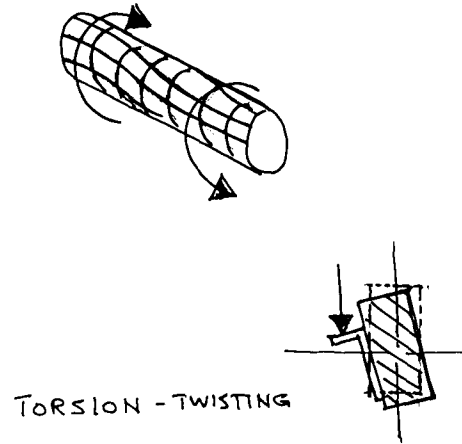
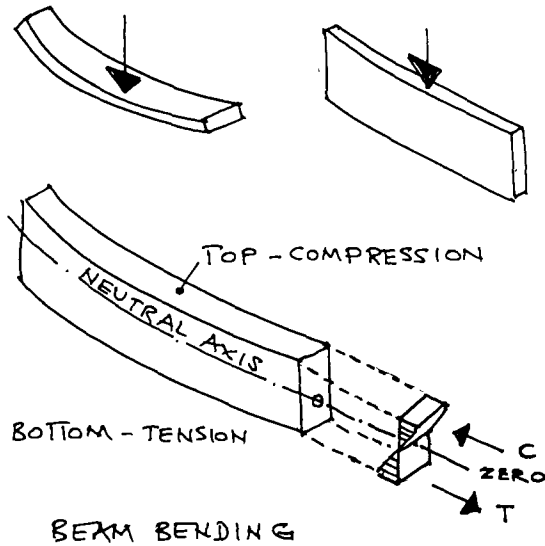
Strain $e = \text{extension per unit length under load}$

$$\frac{\text{Extension}}{\text{Original length}} e = l/L$$

Modulus of elasticity $E = \text{a constant defining the stiffness of a material}$

$$E = \frac{\text{stress}}{\text{strain}}$$

Factor of safety $= \frac{\text{Ultimate stress}}{\text{Working stress}}$



$$\text{STRAIN } e = \frac{l}{L}$$

TENSILE + COMPRESSIVE STRAINS
ARE SIMILAR

SHEAR + TORSIONAL STRAINS
ARE MORE COMPLEX

7

Structural types

Structures can be classified by their basic forms.

Solid Walls, arches, vaults, dams etc.

Surface Grids, plates, shells, stressed skins

Skeletal Trusses and frameworks

Membrane Cable/membrane tents, cable
 nets, pneumatics

Hybrids Tension-assisted structures

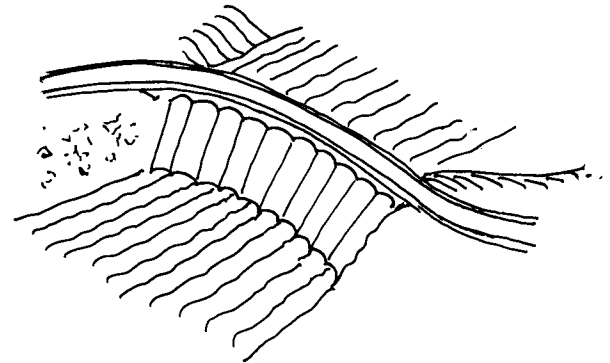
The classifications are not mutually exclusive. For example a thin curved shell dam would be classified as a surface structure.

Combinations of more than one type are common. For example, skeletal frameworks are often stiffened by the insertion of a panel which is a surface structure. Buildings and furniture, aircraft and vehicles are treated in this way. Similarly, monocoque structures are a combination of skin and skeletal.

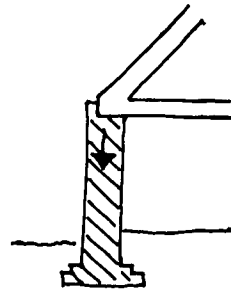
Walls, arches and vaults

Walls are the simplest form of compression structure with loads transmitted vertically downwards. Construction is usually in masonry or concrete. When stiffened with ribs they can also act as retaining structures.

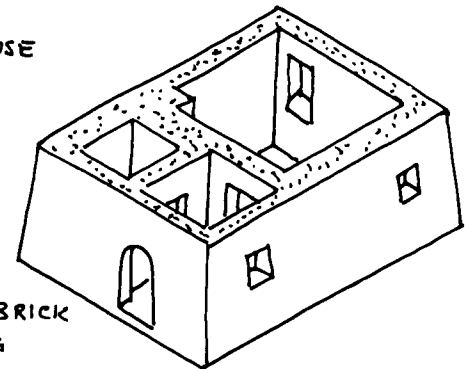
Arches and vaults carry compression loads in a most efficient way due to their curvature. Construction traditionally is in masonry, more recently in reinforced concrete.



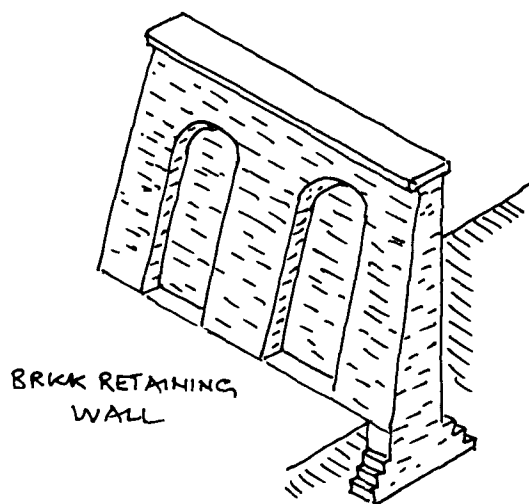
CONCRETE VAULT DAM



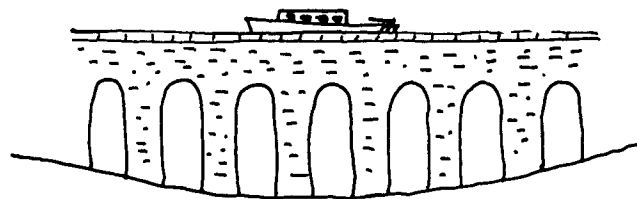
MASONRY HOUSE
WALL



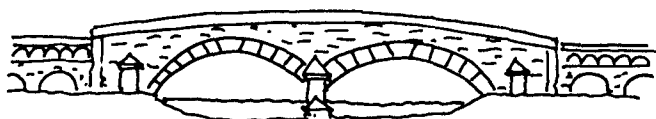
ADOBE MUD BRICK
DWELLING



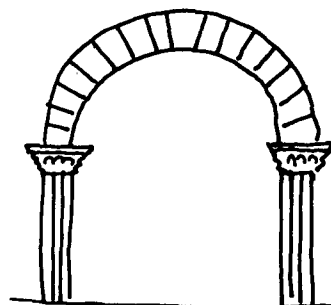
BRICK RETAINING
WALL



BRICK AQUEDUCT ARCHES



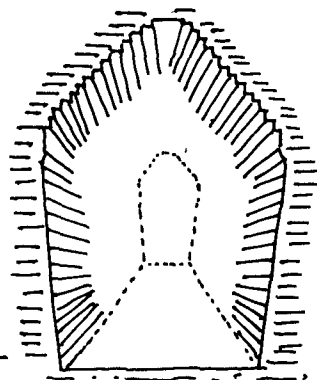
STONE BRIDGE



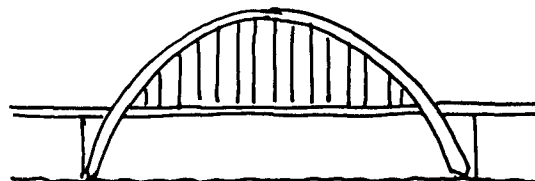
ROMANESQUE ARCH



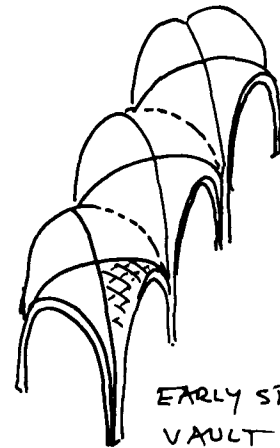
FINIAL



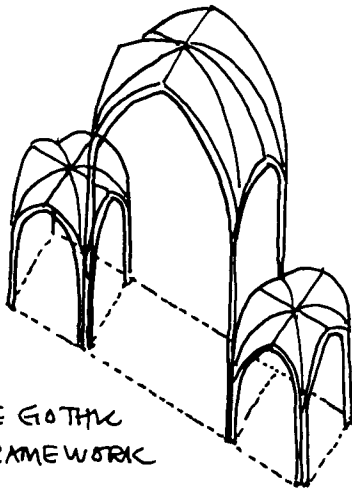
STONE VAULT



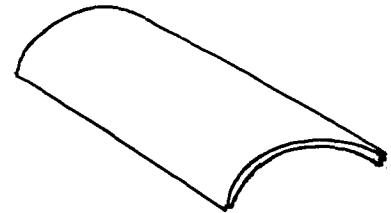
ARCH BRIDGE
(strictly a frame structure)



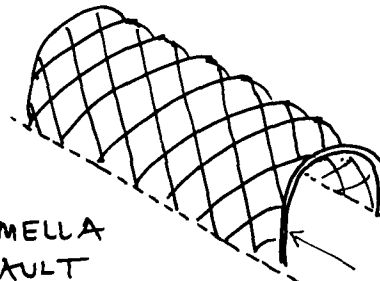
EARLY STONE
VAULT



THE GOTHIC
FRAMEWORK



BARREL VAULT



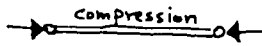
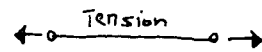
LAMELLA
VAULT
(strictly a surface structure) ARCH

Trusses

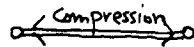
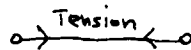
Trusses are an assembly of structural members based on a triangular arrangement with member to member pin-jointed connections called 'nodes'.

Trusses can be two-dimensional (planar) or three-dimensional (prismatic).

Prismatic or space-trusses linked together become space frames.

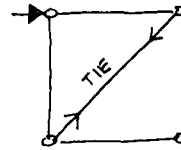


EXTERNAL LOAD

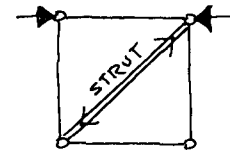


INTERNAL FORCE

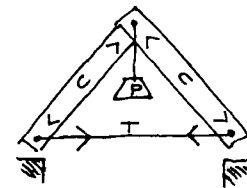
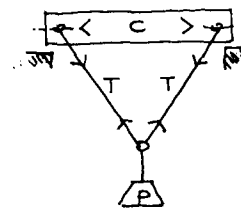
TRUSS SINGLE ELEMENTS



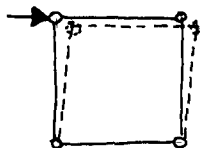
STABLE FOR
ONE LOAD
DIRECTION



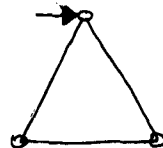
STABLE FOR
BOTH LOAD
DIRECTIONS



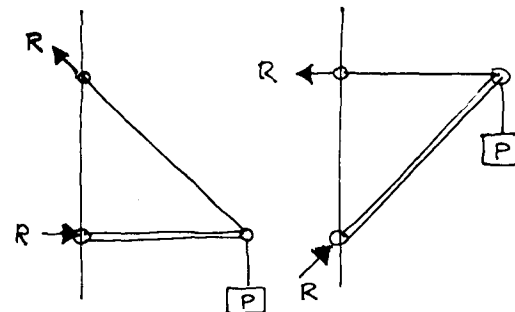
FORCES IN THE SIMPLEST TRUSS FORM



UNSTABLE

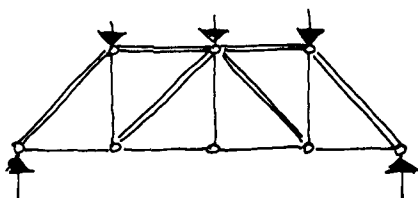
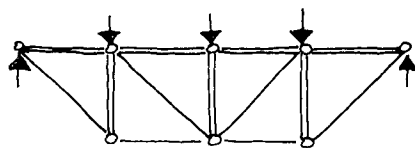
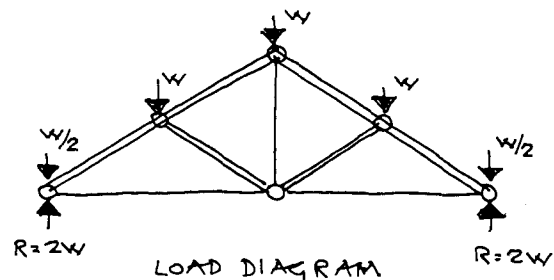
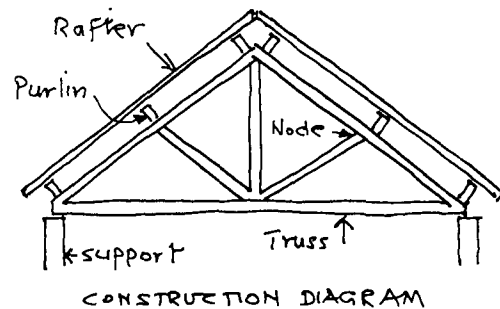
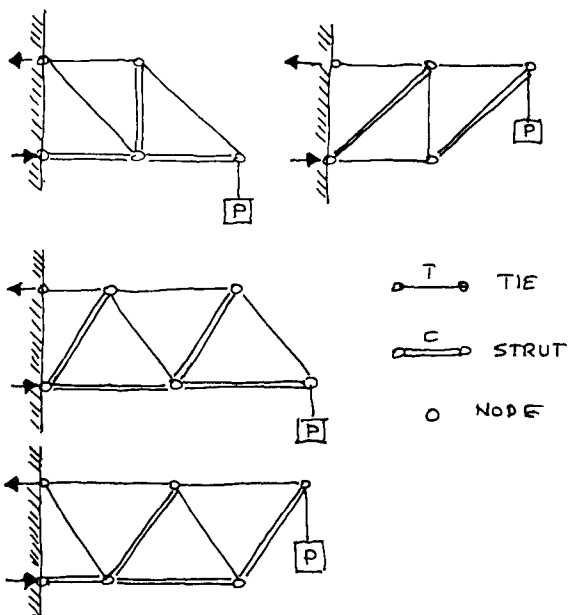


STABLE



TRIANGULATION AND FORCES

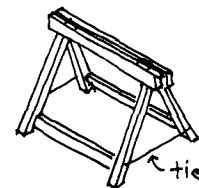
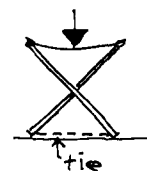
Minimum number of members for stability = 3 linked together

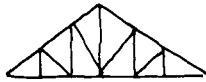


SIMPLE TRUSSES WITH LOADS AND REACTIONS SHOWING TYPE OF FORCE IN MEMBERS



TRIANGULATED STRUCTURES





Howe



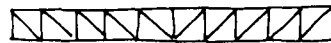
Warren



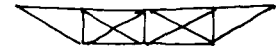
Fink



Pratt



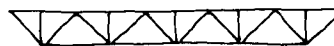
Pratt



Howe



Scissor



Modified Warren



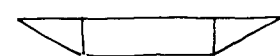
Double Lattice



Bowstring

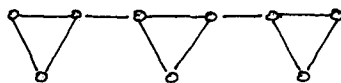


Thrust

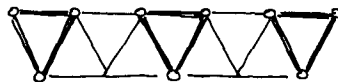


Thrust (not a truss)

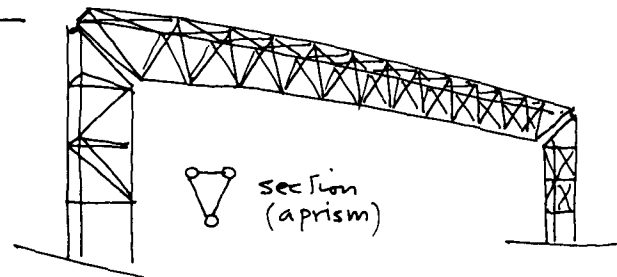
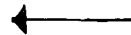
SOME COMMON + NOT SO COMMON TRUSS TYPES



A series linked together



Link a series together with transverse trusses to produce a 2-way lattice structure (space grid)



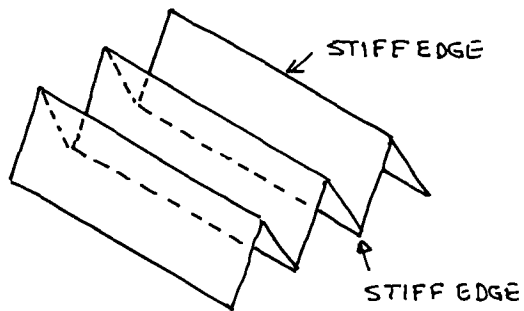
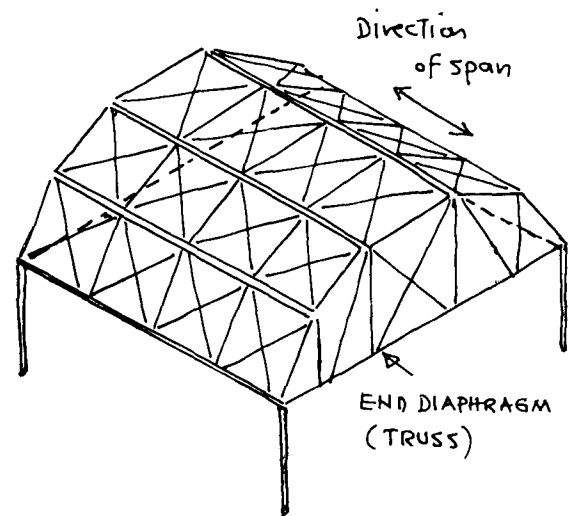
section (a prism)

PRISMATIC LATTICE TRUSS ON PRISMATIC LATTICE COLUMNS

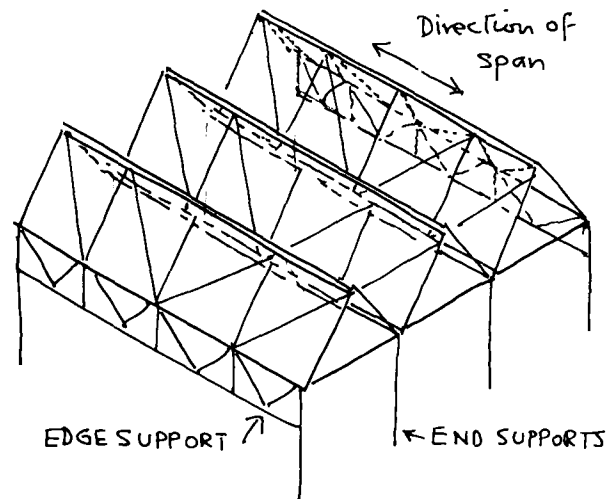
Single-layer lattice grids

Sometimes called single-layer space frames, they are latticed structures with their structural action enhanced by folding. They span longitudinally instead of transversely and are capable of covering quite large areas.

Each fold line acts as a support edge interacting with adjacent planes to prevent deformation.



THE PRINCIPLE OF FOLDING
TO PROVIDE STIFFNESS



Frameworks

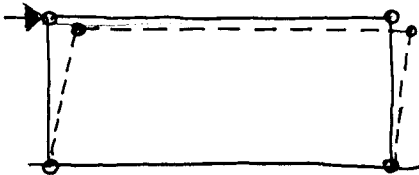
Frameworks are composed of elements which when assembled in two or three directions form a skeletal structure.

The stiffness of a frame depends on the stiffness of the elements and the type of joints between frame members which can be pinned, fixed or partially fixed.

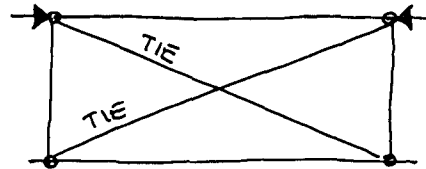
Pinned joint frames are unstable under load and require the addition of a further element to give stiffness: diagonal bracing or stiff panels.

Partially or fully fixed joint frames are stable under load. Loads on beam members cause deflection of the member and rotation of the adjacent joints. This rotation in turn causes deformation of the connected column members and in multi-member frames it becomes a complex problem to analyse. It is now usually solved by computer as the frame is statically indeterminate, i.e. the problem cannot be solved by simple calculations due to the interaction of one member with another through continuity at joint connections.

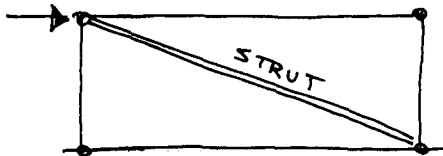
PLANE FRAMES



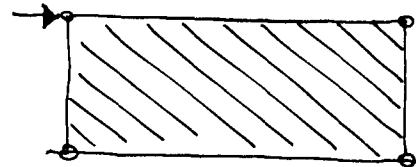
4-PIN JOINTS - MECHANISM
AND $\therefore$ UNSTABLE



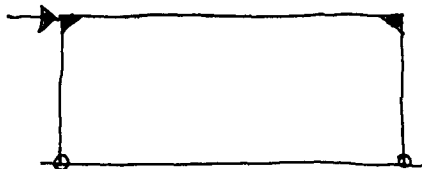
4 PIN JOINTS + 2 TIES



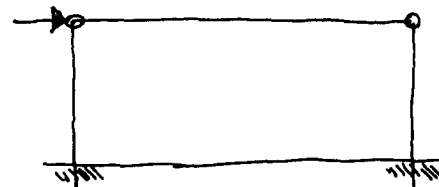
4 PIN JOINTS + 1 STRUT



4 PIN JOINTS + STIFF PANEL

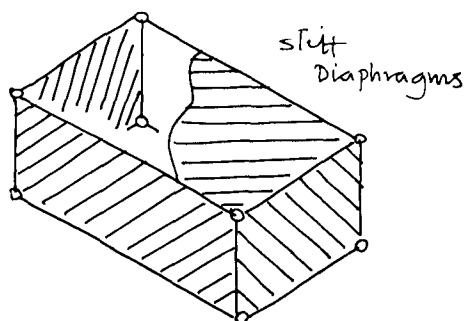
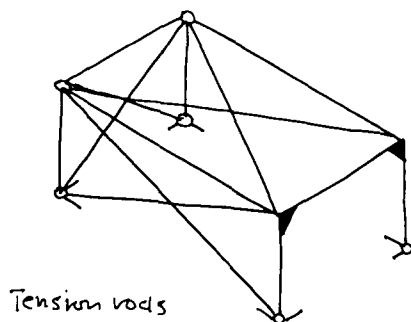
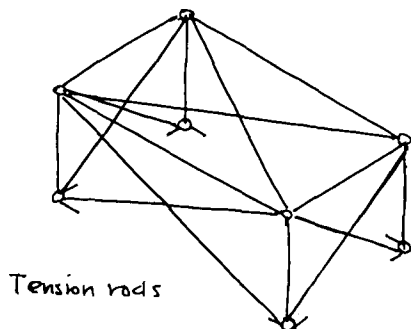


2 PIN JOINTS & 2 STIFF JOINTS

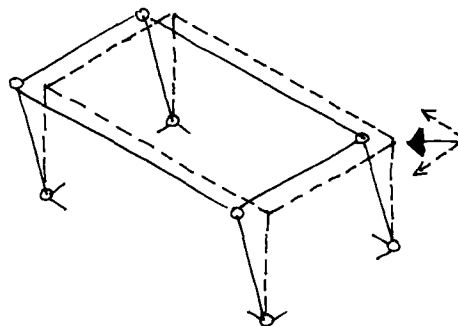


2 PIN JOINTS + 2 FIXED ENDS

BASIC BRACING SYSTEMS



MINIMUM - 3 FACES + TOP BRACED



COLLAPSE DIAGRAM OF ALL PIN-JOINTED FRAME WHICH IS A MECHANISM

BRACING RULES

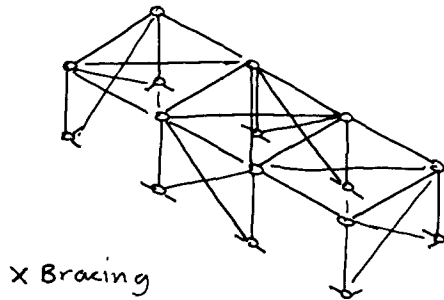
Assume base is a rigid plane

Brace top plane

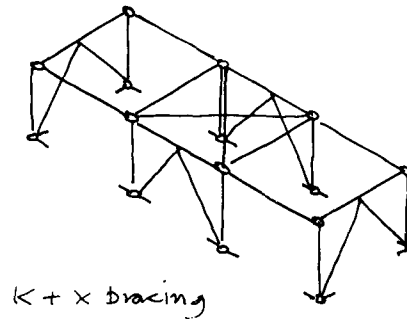
Brace any 3 vertical planes

Use diagonals, stiff diaphragms
or a combination of both

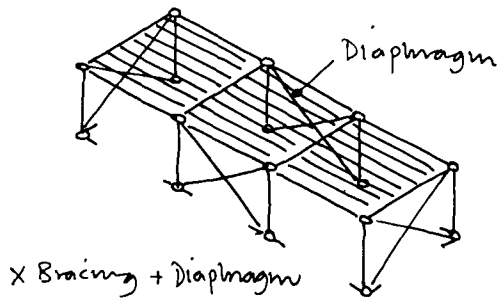
SOME EXAMPLES OF BRACING ALTERNATIVES FOR MULTI-BAYS



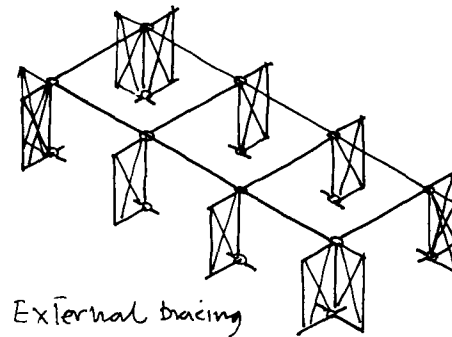
X Bracing



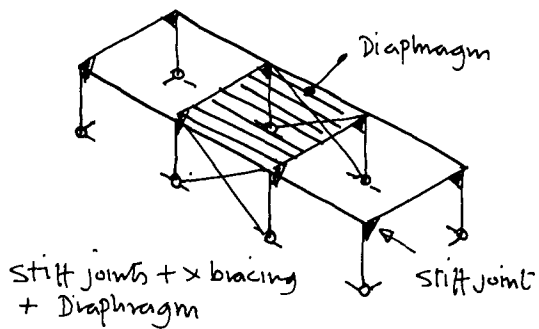
K + X bracing



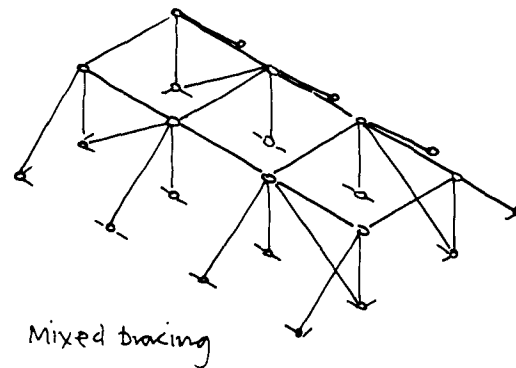
X Bracing + Diaphragm



External bracing



Stiff joints + X bracing + Diaphragm

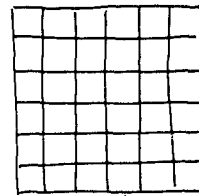


Mixed bracing

Grids

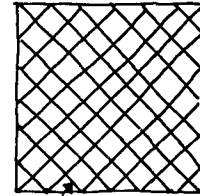
Grids are composed of a series of members arranged at right angles to one another, either parallel to the boundary supports (rectangular grids) or at 45° to the boundary supports (skew grids or diagrids). They behave structurally by load-sharing according to the position and direction of the members close to and further from the position of the load.

The structural analysis of such grids is complicated due to the number of variables involved and therefore is ideal for solution by computer. Grids are commonly used only for large spans where scale economies balance cost and construction complications.



↑
Boundary

RECTANGULAR GRID
(orthogonal)



↑
Beams

SKIEW GRID
(Diagonal)



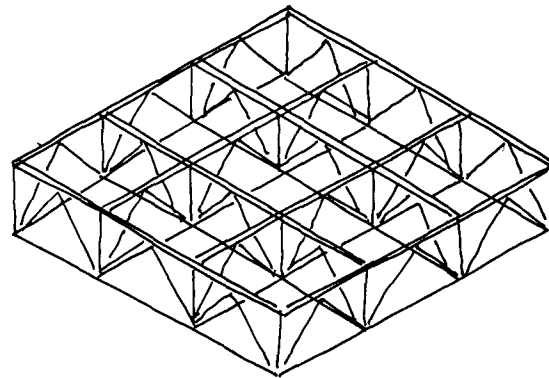
STEEL OR ALLOY



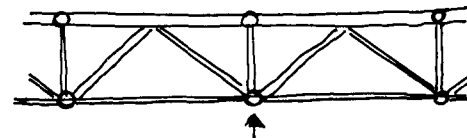
CONCRETE 2-WAY WAFFLE



solid wood ↑ plywood
TIMBER STRESSED SKIN



LATTICE GRID



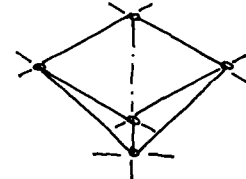
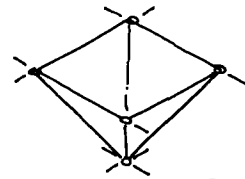
↑
2-WAY LATTICE TRUSSES

Space frames

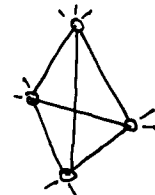
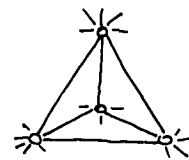
Space frames are three-dimensional lattice structures made up from linked pyramids or tetrahedra into a two-layer or three-layer triangulated framework. Load span and edge conditions determine the form and depth of the space frame. Because of the continuous member linking, optimum load-sharing occurs and for large clear spans – above about 20m, the space frame is a very efficient form of structure with a span/depth ratio of approximately 20:1.

Plan proportions should be near square and not exceed 1.5:1.

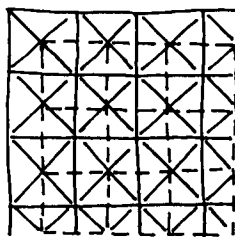
THE BASIC UNIT



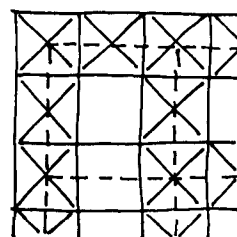
PYRAMID



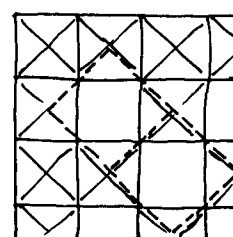
TETRA HEDRON



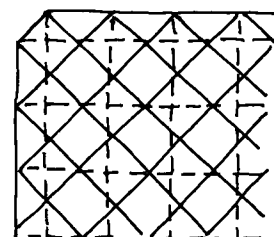
SQUARE ON SQUARE
OFFSET



SQUARE ON LARGER
SQUARE



SQUARE ON
DIAGONAL



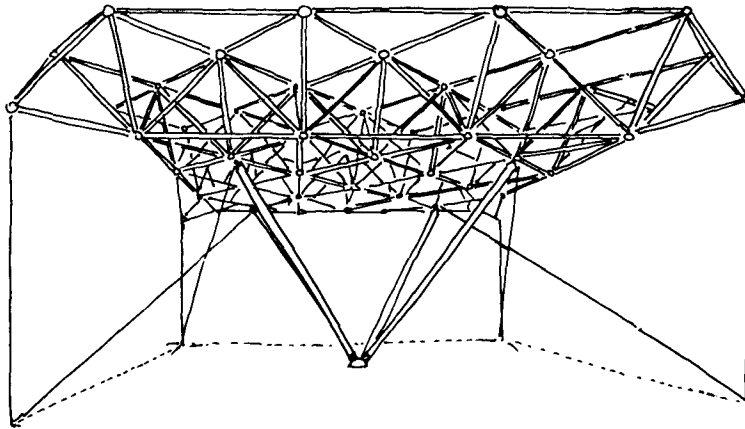
DIAGONAL ON
SQUARE

TYPICAL GRID ARRANGEMENTS

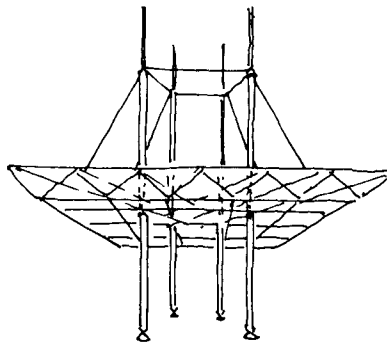
SOME SPACE FRAME SYSTEMS :

NODUS SPACE DECK MERO TRIODETIC OKTAPLATTE UNISTRUT SDC

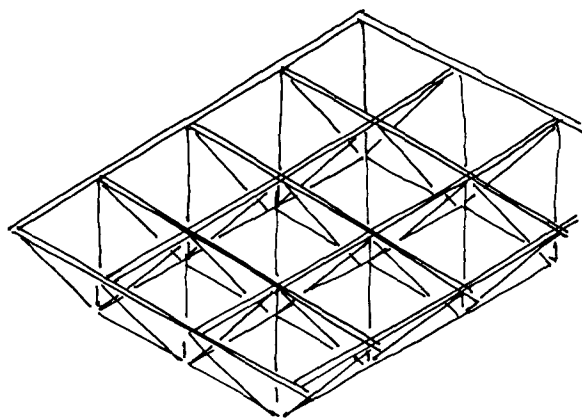
↑ OUT OF PRODUCTION



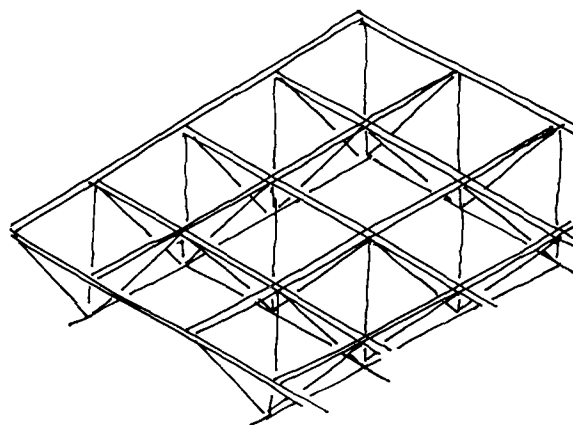
SPACE FRAME - LONDON ZOO
Centrally supported with tension cables for stability



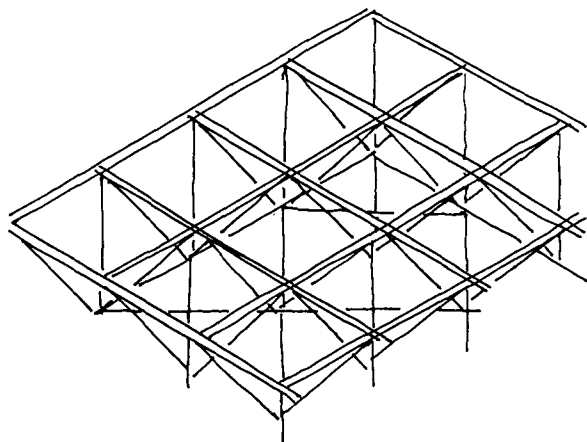
CABLE + MAST SUPPORTED SPACE FRAME
AS ENTRANCE CANOPY



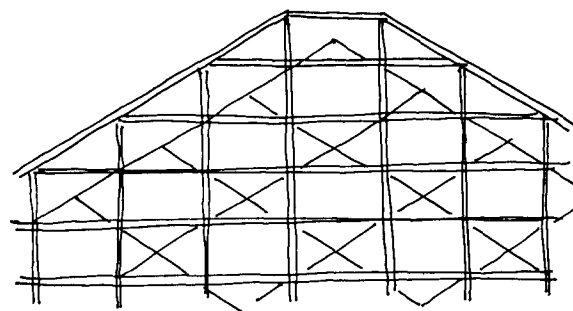
SQUARE ON SQUARE



SQUARE ON LARGER SQUARE



SQUARE ON DIAGONAL



DIAGONAL ON SQUARE

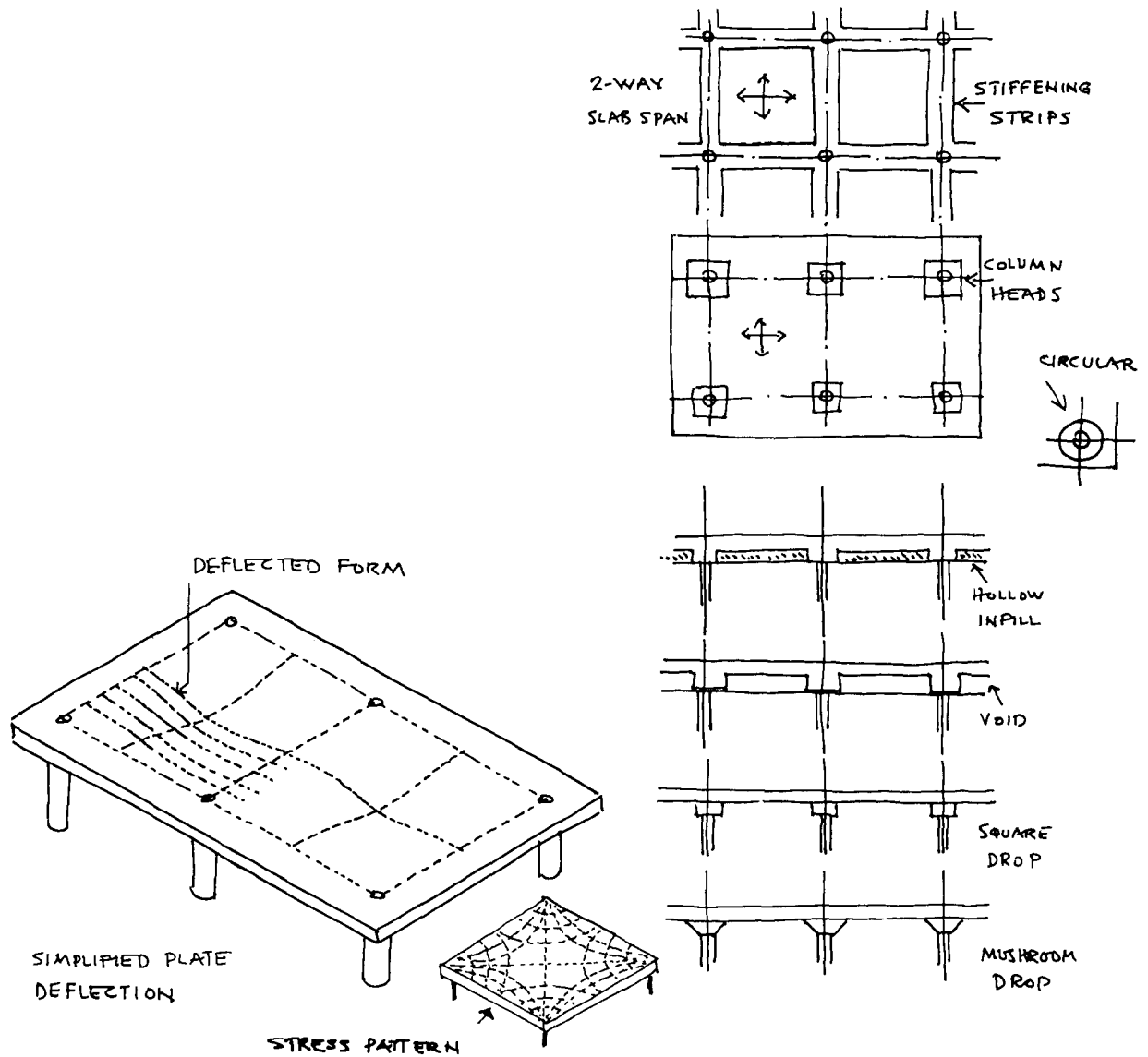
SPACE FRAME GRIDS

Plates

Plates or flat slabs are generally horizontal elements with a length and breadth which are large in comparison with their thickness – span to depth up to 40:1. They are designed to span in two directions at right angles and may be flat, have stiffening strips or thickening at supporting column points.

Multi-bay plates are statically indeterminate and are calculated by textbook design factors or computer.

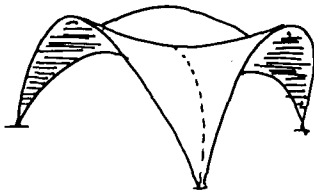
Slabs can be designed around lines of equal stress but formwork is elaborate and thus expensive (cf the work of Pier Luigi Nervi).



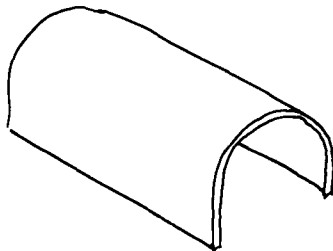
Shells

Shells are surface structures which are curved in one of two directions or are warped as in the hyperbolic paraboloid shell.

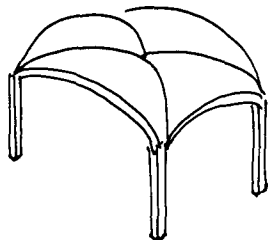
Structural forces in shells are largely pure tension and compression.



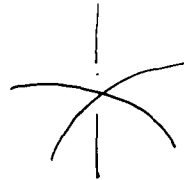
HYPERBOLIC PARABOLIC SHELL



CYLINDRICAL SHELL
- Barrel vault



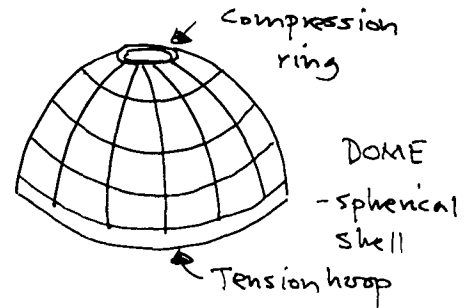
ELLIPSOID VOLT -
Elliptic paraboloid



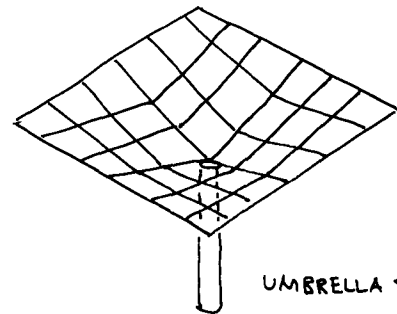
Synclastic
Curvature



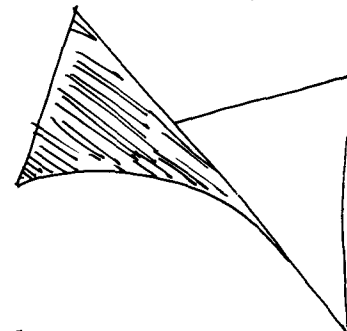
Anticlastic
Curvature



DOME
- spherical
shell



UMBRELLA SHELL
- hyperbolic paraboloid



SADDLEBACK SHELL
- Hypar

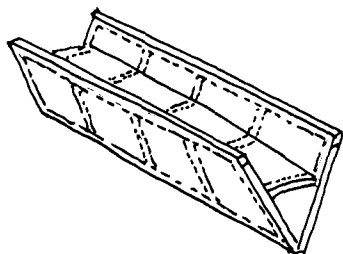
Stressed skins

A combination of thin plates with rib-stiffeners is a stressed skin surface.

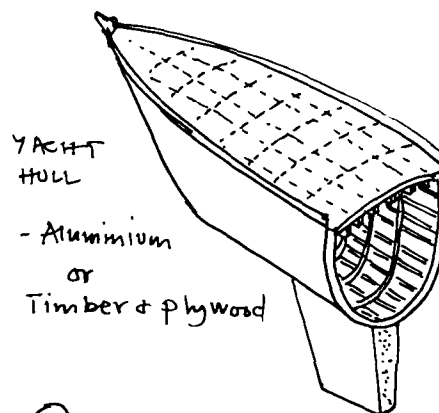
The ribs contribute stiffness to what would otherwise be a too thin and flexible sheet material, which under load would buckle.

The material used for stressed skin construction can be metal, timber, GRP, or sometimes a combination (e.g. 'Nomex' – see composite material panels).

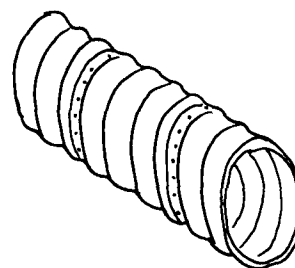
Analysis of stressed skins is carried out by computer or by testing, according to the complexity of the problem since this structure is statically indeterminate.



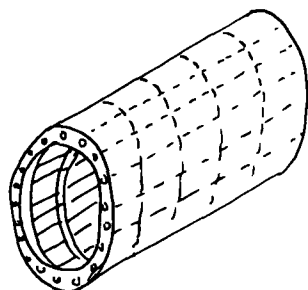
STRESSED SKIN STEEL BRIDGE



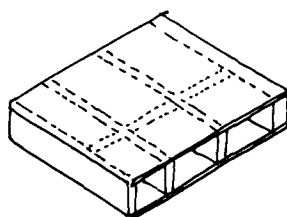
YACHT
HULL
- Aluminium
or
Timber & plywood



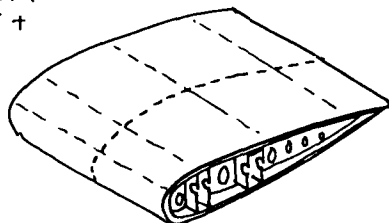
CORRUGATED
STEEL TUBE
(SILO OR TUNNEL)



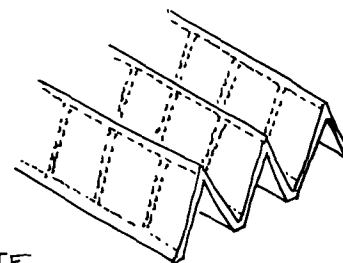
ALUMINIUM
FUSELAGE +
WING



PLYWOOD / SOFTWOOD
PANEL



CONCRETE
FOLDED PLATE ROOF
ALSO IN PLYWOOD



SEE ALSO
SINGLE LAYER GRIDS

Membranes

In membrane structures all the primary forces are arranged to be in tension, either in the form of cables forming a net or by means of a coated fabric with tensioned edge cables. Loads from the membrane can be taken to the ground via compression masts with perimeter anchor cables or by some other form of aerial structure.

Stress concentrations tend to occur at the boundaries and curved cables are often introduced to even them out (tear drops and zigzags at the mast top, boundary cables at the edge). Curvature of the surface must be maintained in two directions (anticlastic) otherwise flutter will occur under wind load and failure may result.

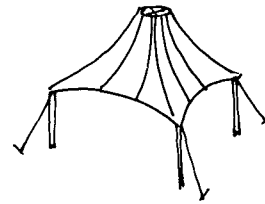
Pneumatics are air supported membranes usually without any other form of structure required to support them, except a foundation ring beam to act as an anchor.

There are a number of fabric types in use and others constantly under development. The three typical ones in current use are:

Polyvinyl chloride coated polyester – PVC polyester

Polytetrafluoroethylene coated glass fibre – PTFE glass

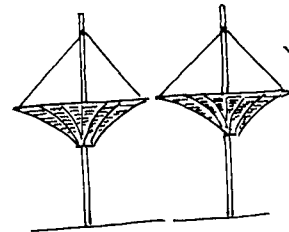
Ethylene-tetra-fluoroethylene foil – ETFE foil



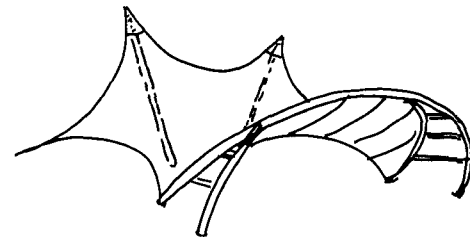
FABRIC CONE



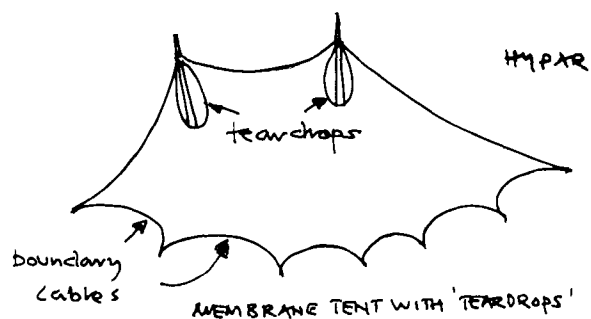
HYPAR FABRIC TENT



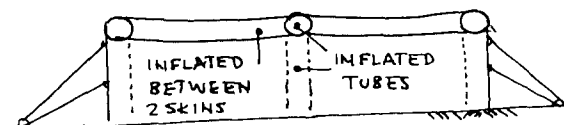
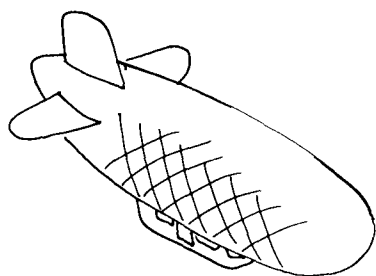
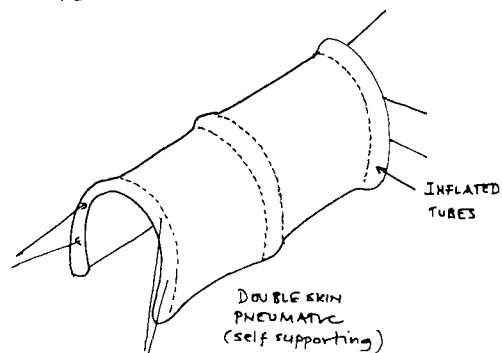
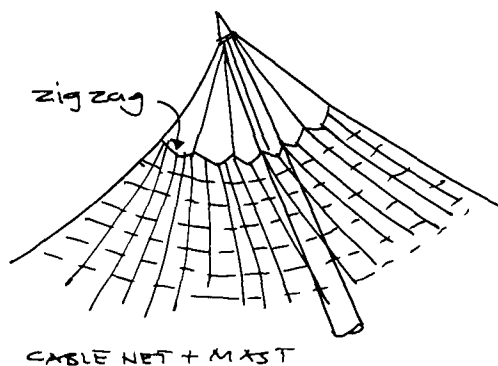
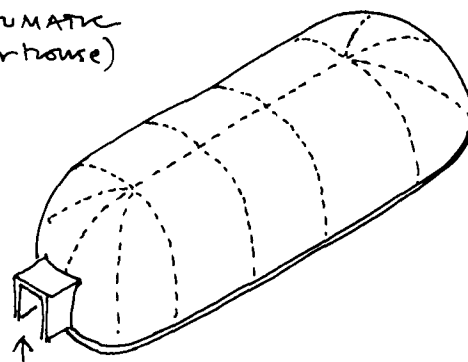
INVERTED FABRIC CONES
STEEL MASTS



MAST + ARCH SUPPORTED MEMBRANE



SINGLE SKIN
PNEUMATIC
(Air house)



Hybrids

There are a number of structural types which do not fit into any of the four previous classifications and these are defined as hybrids. It is a fact that although the primary type may be 'solid', 'skeletal' etc., secondary elements of a different type may be part of the structure. The hybrid is where there is a combination of two types of near equal dominance.

Many tension-assisted structures fall into this category and typically will consist of the following combinations:

Steel and tensile membrane

Structural glass and steel

Masonry and steel

Timber/plastic and steel

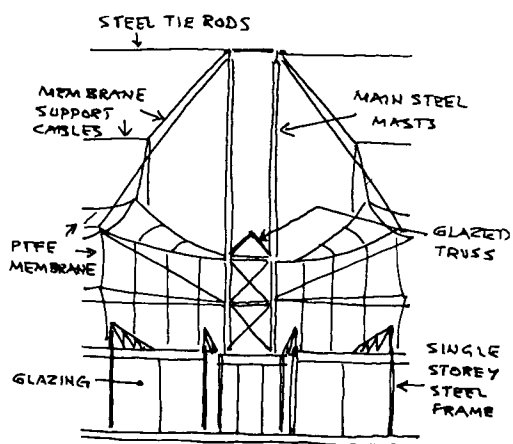
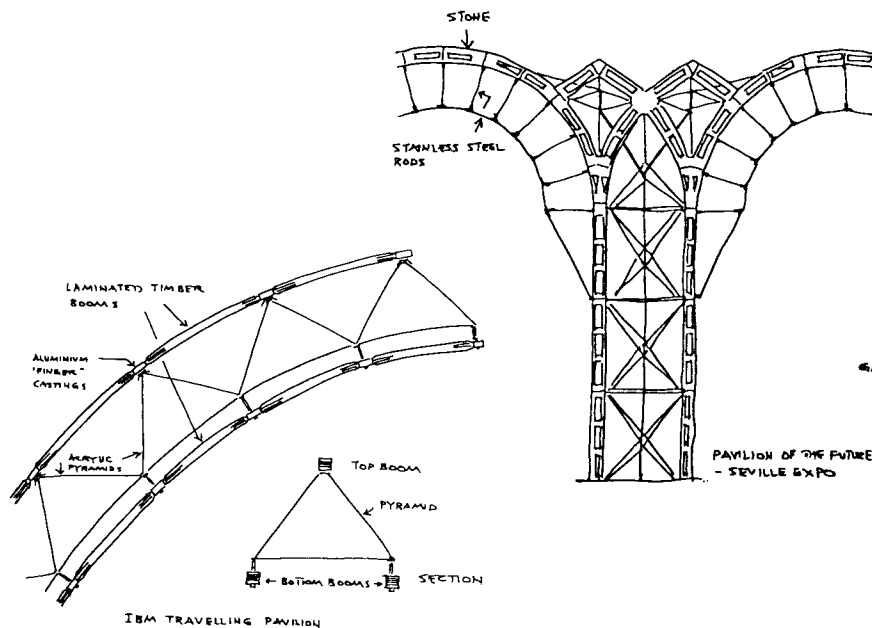
Examples of the above, in order, are as follows:

Schlumberger Cambridge Research –
Cambridge

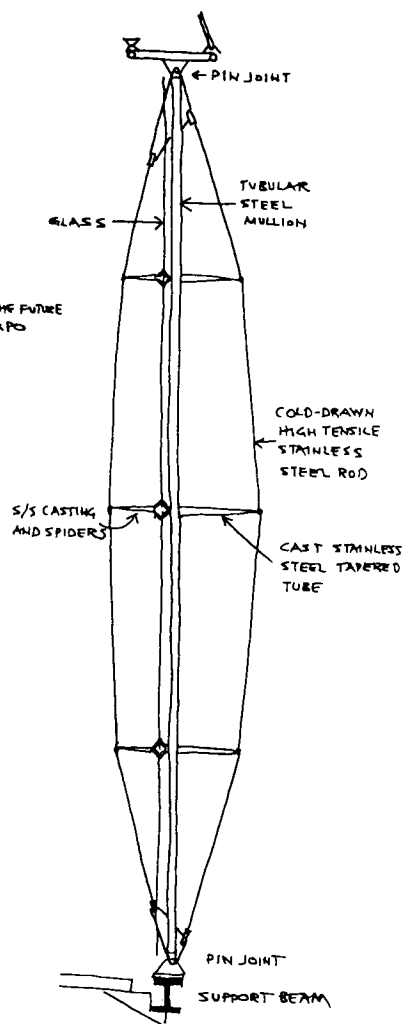
Waterloo International Station Concourse Wall

Pabellón de Futur-Seville Expo

IBM Travelling Exhibition



SCHLUMBERGER CAMBRIDGE RESEARCH



WATERLOO INTERNATIONAL - CONCOURSE WALL

8

Some further significant structures and assemblies

A detailed look at the work of well-known engineers throws up a number of original and inventive solutions for both complete structural assemblies and structural parts.

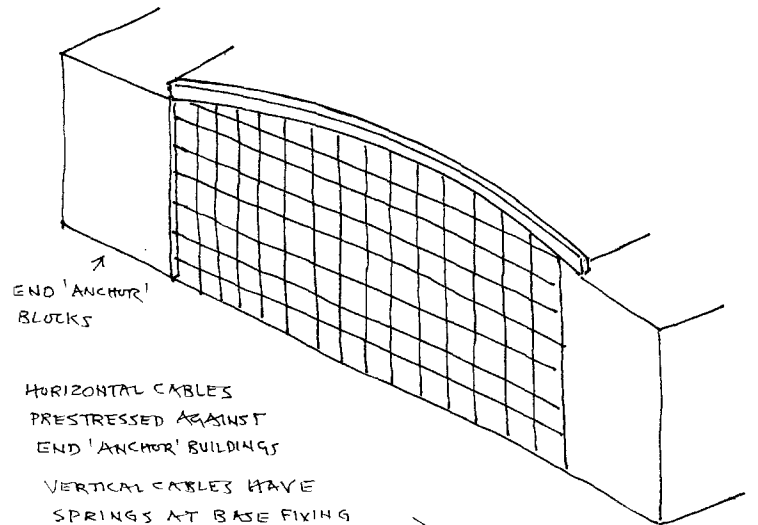
As with hybrids in Chapter 7, these designs are difficult to classify. They are always a combination of, at least, tension and compression. They can, however, be put into categories and these are listed with the relevant structures illustrated.

Primary tension

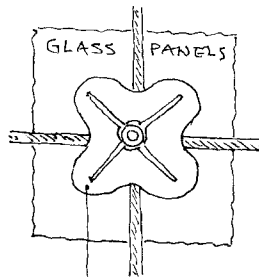
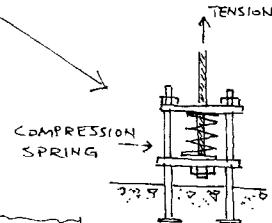
Kempinski Hotel, Munich

ETFE Foil 'Pillow' – Eden Project

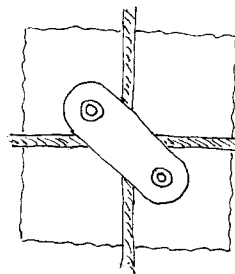
Parc de la Villette, Paris –
Cable Trussed Glass Wall



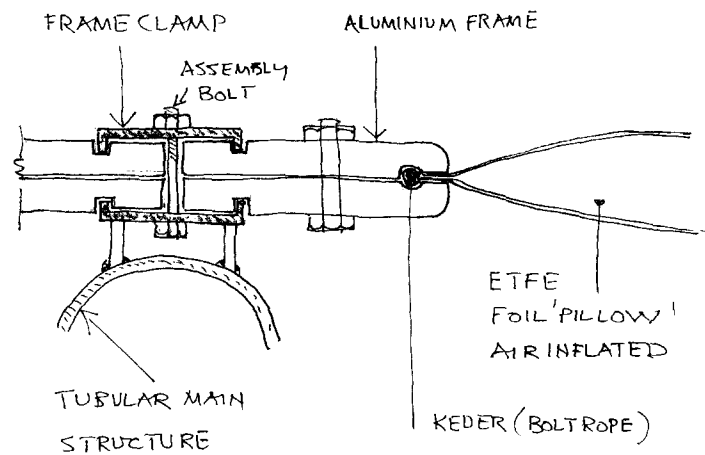
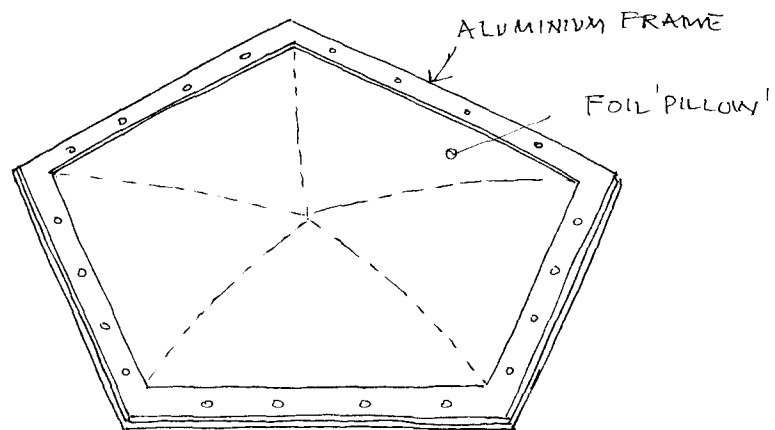
STEEL CABLE AND GLASS FAÇADE
40M WIDE X 25M HIGH



GLASS CLAMPING PLATE
WITH NEOPRENE PADS
AND BACK PLATE

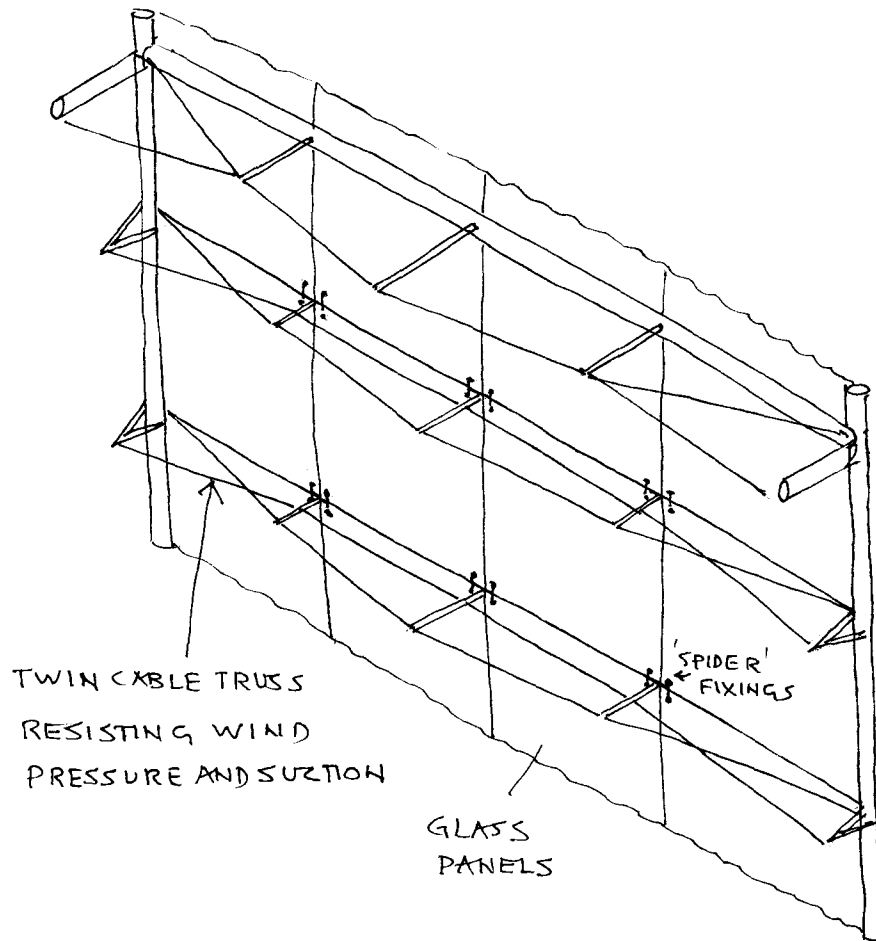


CABLE CLAMPING PLATE
IN TWO PARTS WITH GROOVES
FOR CABLES



EDEN PROJECT - CORNWALL

ETFE FOIL PILLOW AND ALUMINIUM CLADDING



PARC de la VILLETTE - PARIS
CABLE TRUSSED GLASS WALL

Tension and compression

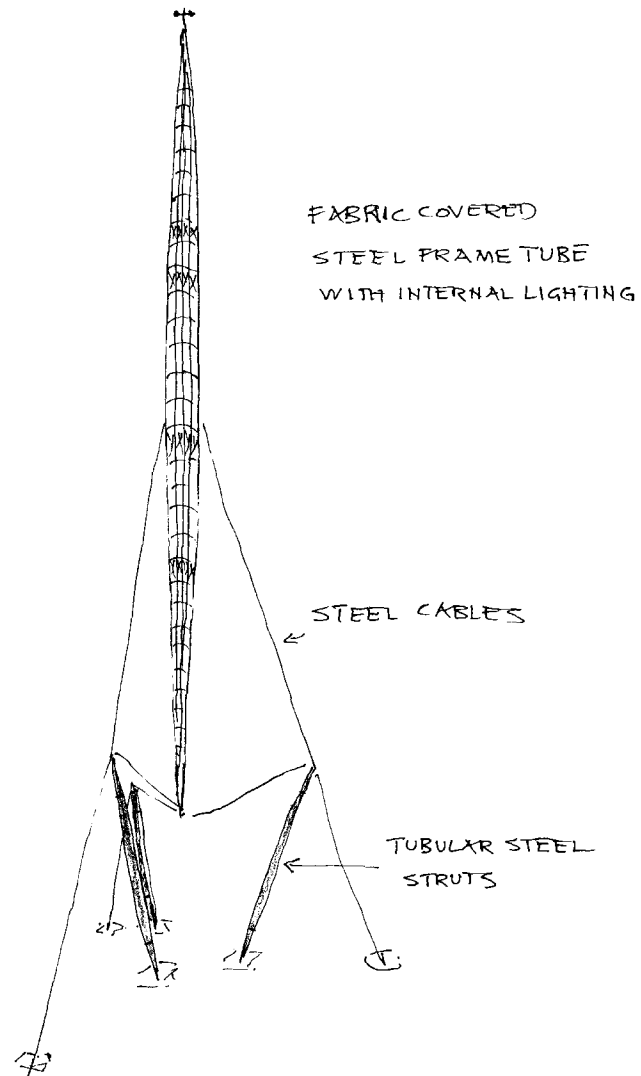
The Skylon – Festival of Britain
1951

Visionary Structures – Robert le
Ricolais

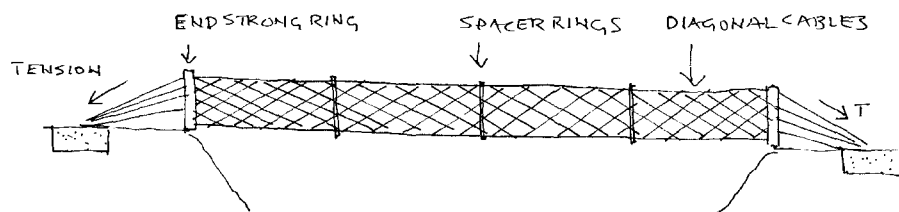
Hong Kong Aviary

International Conference
Centre, Paris – fully adjustable
main glazing bracket

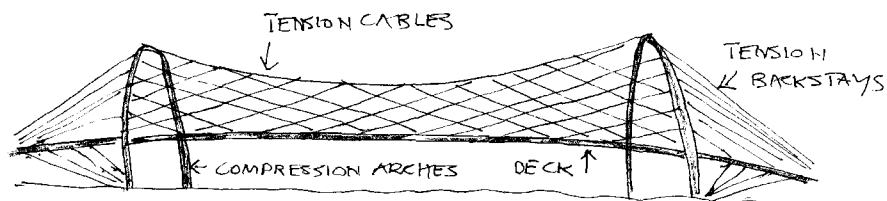
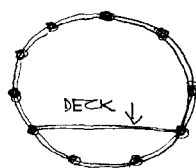
Stuttgart 21 – Station Roof
Structure



THE SKYLON - FESTIVAL OF BRITAIN · LONDON 1951
AN EARLY EXAMPLE OF A TENSEGRITY STRUCTURE

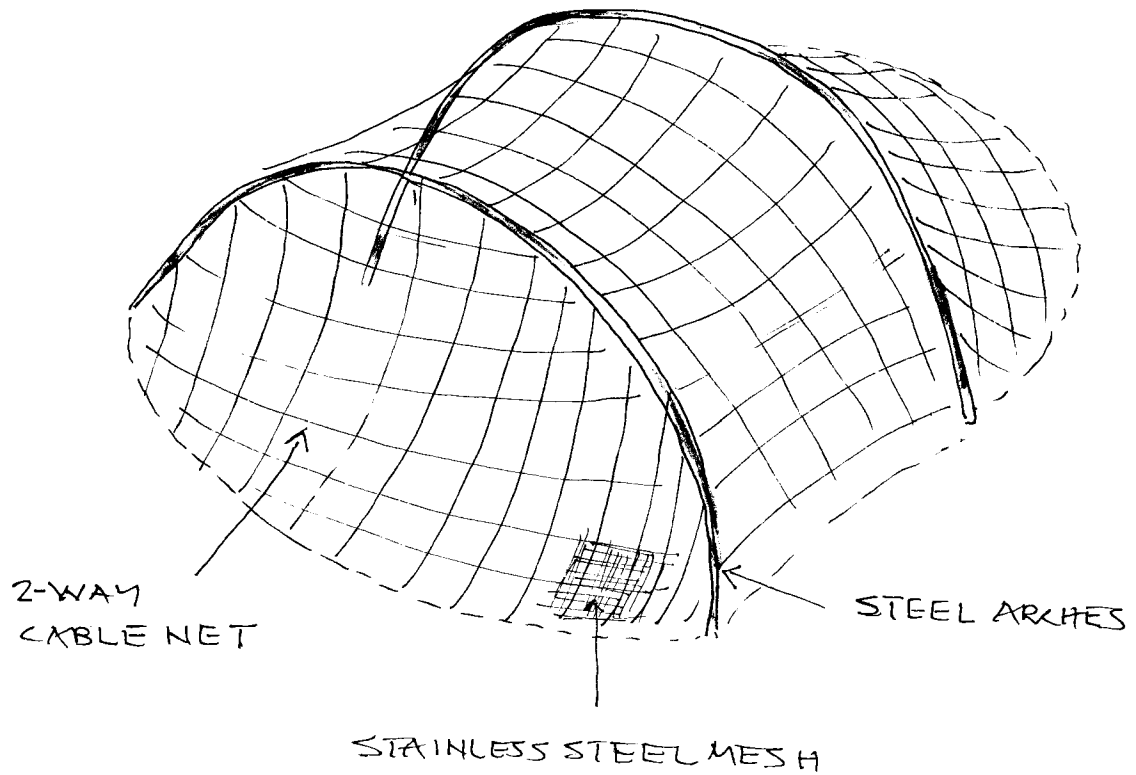


'HOLLOW ROPE'
BRIDGE

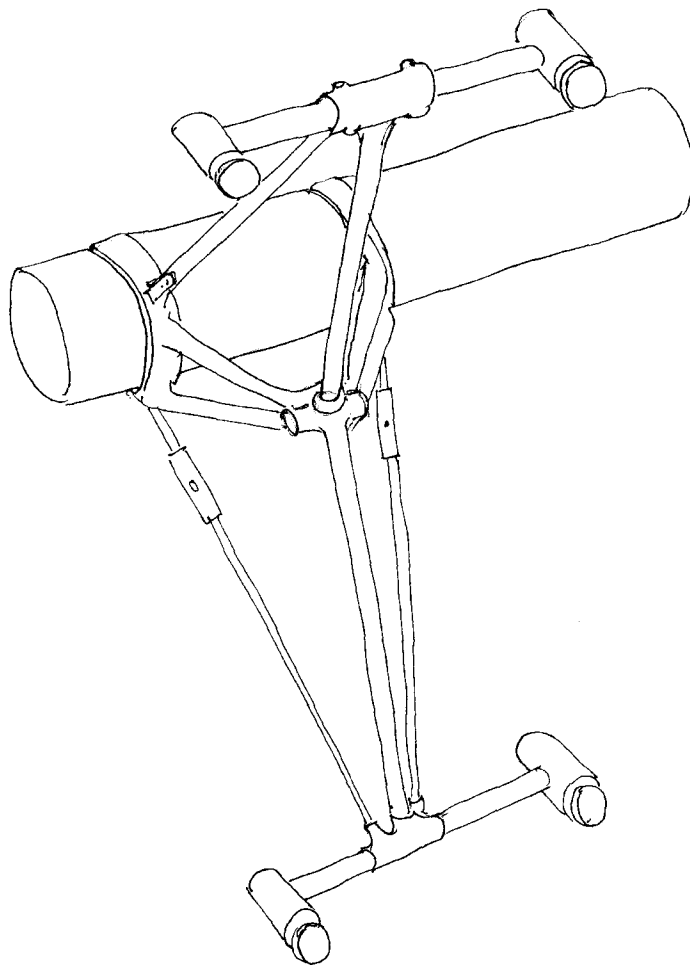


'HOLLOW ROPE SUSPENSION BRIDGE

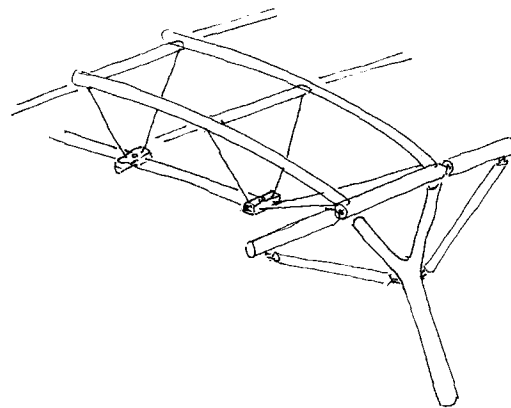
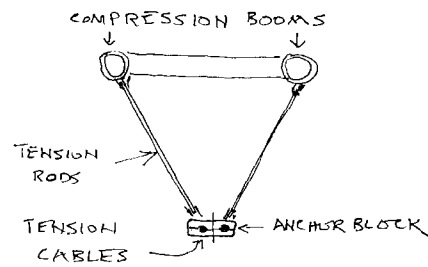
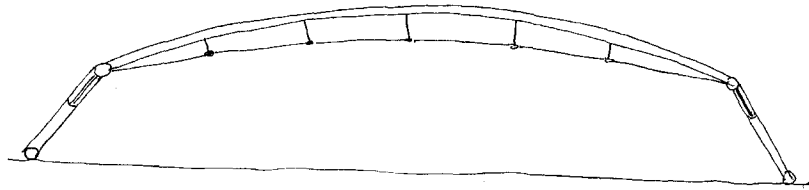
TWO EXAMPLES OF ROBERT LE RICOULAS'
'VISIONARY' STRUCTURES



HONG KONG AVIARY



INTERNATIONAL CONFERENCE CENTRE - PARIS
FULLY ADJUSTABLE MAIN GLAZING BRACKET



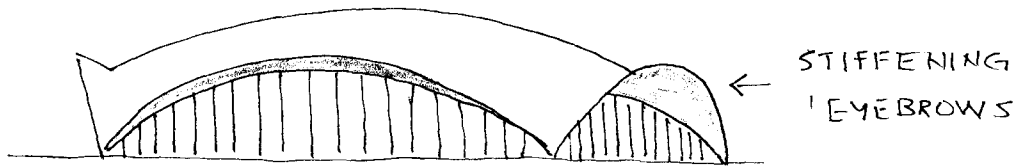
STUTTGART 21 - STATION ROOF STRUCTURE

Primary compression

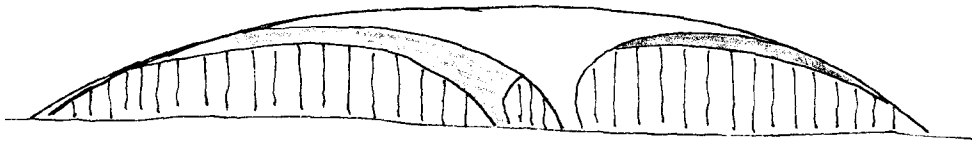
Thin Concrete Shells – Switzerland

Geodesic Domes – Eden Project,
Cornwall

Compression Arch and Joint –
National Botanic Garden of Wales

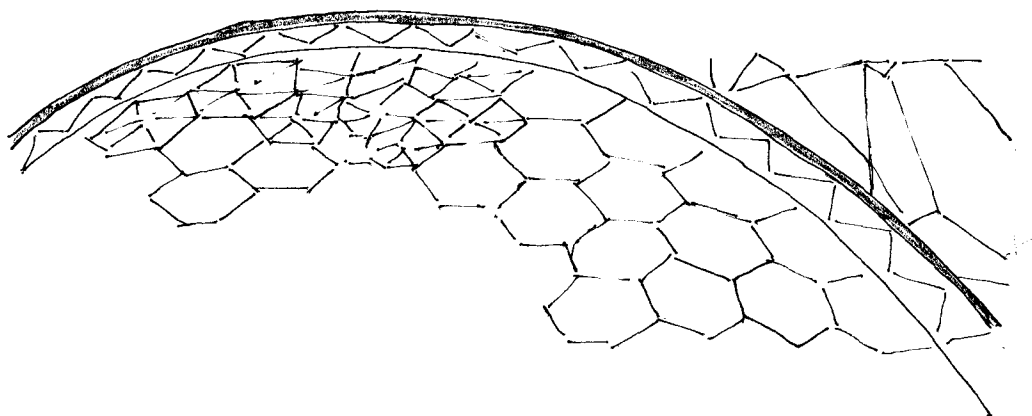


CONCRETE SHELL - GARDEN CENTRE - PARIS



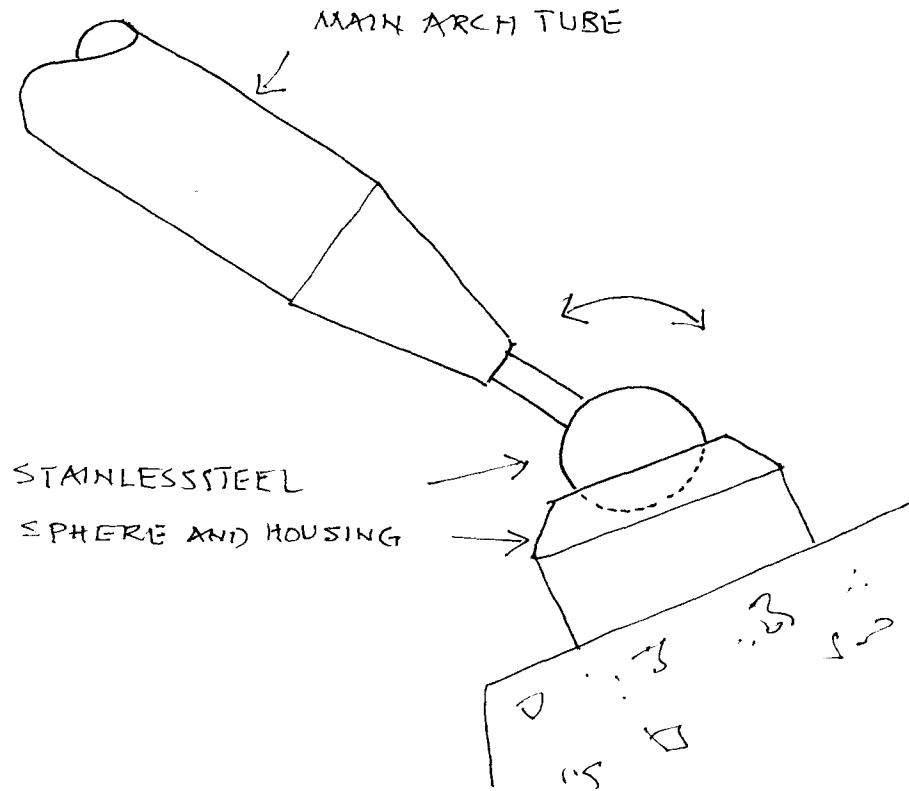
KILCHER FACTORY NEAR SOLOTHURN - CONCRETE SHELL

EXAMPLES OF EXTREMELY THIN CONCRETE SHELLS



EDEN PROJECT - CORNWALL

PART OF A MAIN GEODESIC DOME
AND SUPPORTING ARCH



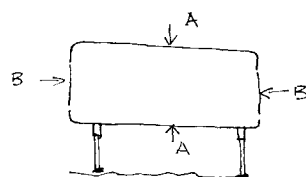
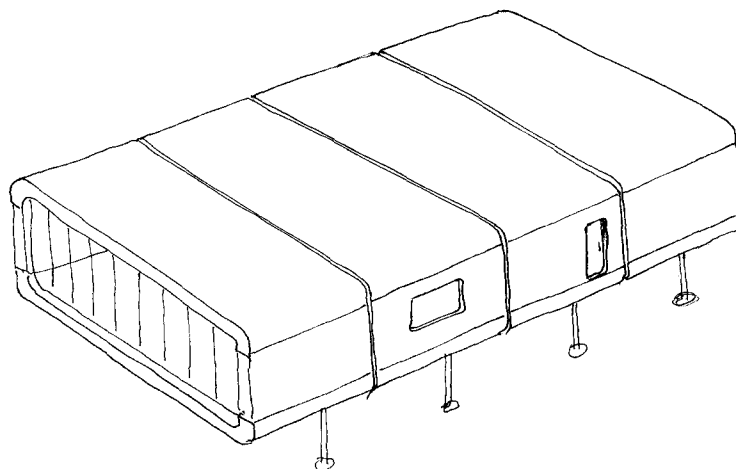
NATIONAL BOTANIC GARDEN OF WALES

MAIN ARCH BEARING IN STAINLESS STEEL

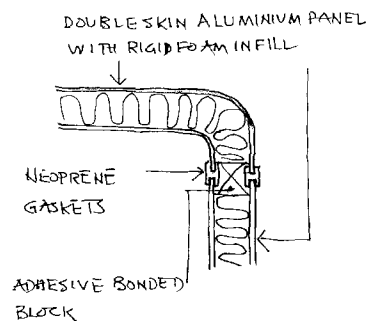
IT ALLOWS ROTATION DUE TO TEMPERATURE
VARIATION [THERE IS NO UPLIFT!]

Composite

DuPont Competition – 'Zip-Up' House



TYPE A - ROOF and FLOOR
TYPE B - WALLS



DUPONT COMPETITION - 'ZIP-UP' HOUSE [1966]

AN EARLY EXAMPLE OF MONOCOQUE REPETITION
FOR BATCH PRODUCTION

Appendices

Appendix I: Tensile strength of some common materials

Material	Tensile strength – S		
	lb/in ²	MN/m ²	Relative strength
Cement and concrete	600	4.1	0.6
Ordinary brick	800	5.5	0.8
Fresh tendon (animal)	12,000	82	12
Hemp rope	12,000	82	12
Wood (air dry) along grain	15,000	103	15
Wood (air dry) across grain	500	3.5	0.5
Fresh bone	16,000	110	16
Ordinary glass	5,000–25,000	35–175	5–25
Human hair	28,000	192	28
Spider's web	35,000	240	35
Good ceramics	5,000–50,000	35–350	5–50
Silk	50,000	350	50
Cotton fibre	50,000	350	50
Catgut	50,000	350	50
Flax	100,000	700	100
Glassfibre plastics	50,000–150,000	350–1,050	50–150
Carbon fibre plastics	50,000–150,000	350–1,050	50–150
Nylon thread	150,000	1,050	150

Tensile strength of some common materials (cont'd)

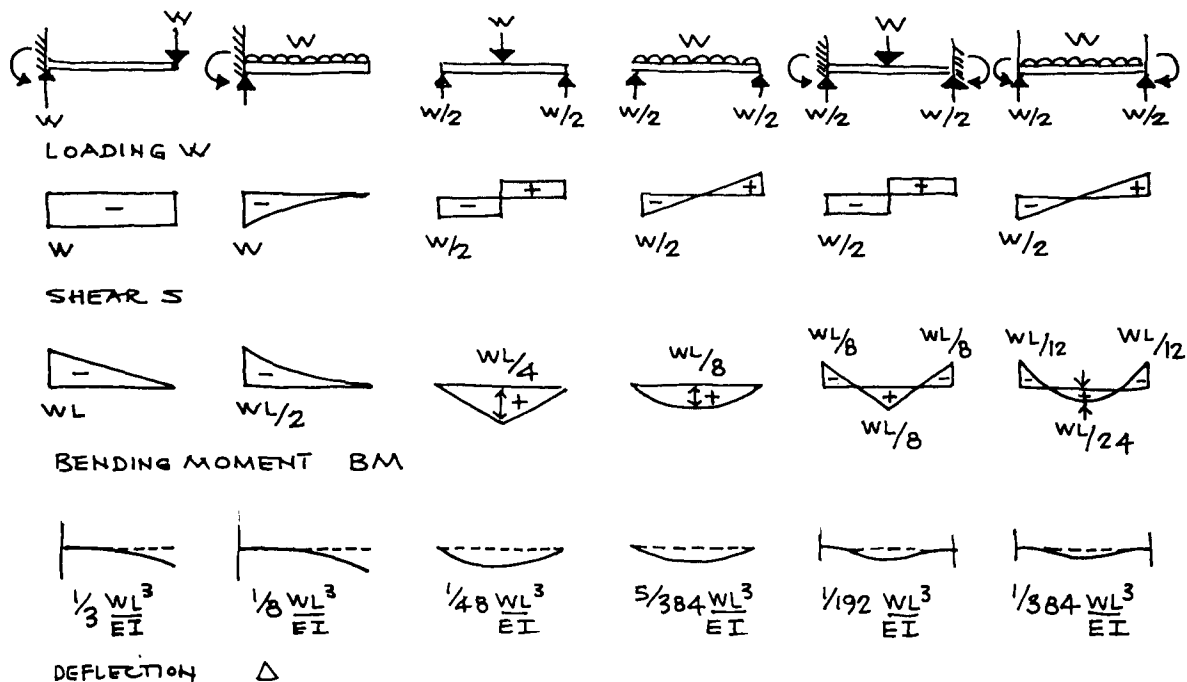
Material	Tensile strength—S		
	lb/in ²	MN/m ²	Relative strength
Steel piano wire (very brittle)	450,000	3,100	450
High tensile engineering steel	225,000	1,550	225
Commercial mild steel	60,000	400	60
Traditional wrought iron	15,000–40,000	100–300	15–40
Traditional cast iron (very brittle)	10,000–20,000	70–140	10–20
Modern cast iron	20,000–40,000	140–300	20–40
Aluminium: cast	10,000	70	10
Aluminium: wrought alloys	20,000–80,000	140–600	20–80
Magnesium alloys	30,000–40,000	200–300	30–40
Titanium alloys	100,000–200,000	700–1,400	100–200
Carbon fibre (high strength)	270,000	4,000	270
Kevlar 49	270,000	4,000	270

***E* values for some common materials**

Material	<i>E</i> value		
	lb/in²	MN/m²	Relative stiffness
Rubber	1,000	7	1
Shell membrane of an egg	1,100	8	1.1
Human cartilage	3,500	24	3.5
Human tendon	80,000	600	80
Wallboard	200,000	1,400	200
Unreinforced plastics, polythene and nylon	200,000	1,400	200
Plywood	1,000,000	7,000	1,000
Wood (along grain)	2,000,000	14,000	2,000
Fresh bone	3,000,000	21,000	3,000
Magnesium metal	6,000,000	42,000	6,000
Ordinary glass	10,000,000	70,000	10,000
Aluminium alloys	10,000,000	70,000	10,000
Brasses and bronzes	17,000,000	120,000	17,000
Kevlar 49	19,000,000	130,000	19,000
Iron and steel	30,000,000	210,000	30,000
Carbon fibre (high strength)	60,000,000	420,000	60,000
Aluminium oxide (sapphire)	60,000,000	420,000	60,000
Diamond	170,000,000	1,200,000	170,000

Appendix II: Bending and deflection formulae for beams

SHEAR BENDING AND DEFLECTION DIAGRAMMS FOR SOME STANDARD CASES



RELATIVE STIFFNESSES ARE INVERSELY PROPORTIONAL TO MAX. DEFLECTION

1 2.6 16 25.6 64 128

RELATIVE STRENGTHS ARE INVERSELY PROPORTIONAL TO MAX. BENDING MTS.

1 2 4 8 8 12

Appendix III: Reading list

Bill Addis, *The Art of the Structural Engineer*,
Artemis

Some philosophy and a wide range of recent case studies of building structure in all materials

Allen Andrews, *Back to the Drawing Board: The Evolution of Flying Machines*,
David & Charles

Drawings, models, photographs and text from before the birth of the lighter-than-air machine to nearly the present. A must for anyone interested in aircraft development

Fred Angerer, *Surface Structures in Building*,
Alec Tiranti

Probably the best non-mathematical book on surface structures, with excellent diagrams

Cecil Balmond with Jannuzzi Smith, *'Informal'*,
Prestel

A book by an engineer who collaborates with architects in creating 'non-cartesian' free-form structures. The book is part engineering, part mathematics and part philosophy and outlines a different approach to structural thinking

Derrick Beckett, *Bridges*, Paul Hamlyn
A very good general view

Behnisch/Hartung, *Eisenkonstruktionen Des 19 Jahrhunderts* (in German), Schiriner/
Mosel

Comprehensive coverage of nineteenth-century iron and steel engineering and architecture

Adriaan Beukers and Ed van Hinte, *Lightness – the Inevitable Renaissance of Minimum Energy Structures*,

010 publishers, Rotterdam

Essential reading for any designer interested in ways of using 'smart' materials in the most economical way. It has some very revealing examples and statistics. Based on research carried out at the Faculty of Aerospace Engineering, Delft Technical University

John Borrego, *Space Grid Structures*,
MIT Press

A comprehensive catalogue of three-dimensional structures, with good diagrams and photographs of models

Alan J Brookes and Chris Grech, *The Building Envelope*, Butterworth Architecture

Isambard Kingdom Brunel, *Recent Works*, Design Museum

Analysis and drawings by practising architects and engineers of a number of Brunel's famous works including the Royal Albert Bridge at Saltash, the *Great Eastern* and Paddington Station

Santiago Calatrava, *The Daring Flight*, Electa

Centre George Pompidou/Le Moniteur, *l'art de l'ingénieur*

A biography of engineering and engineers worldwide. Only published in French

Connections – *Studies in Building Assembly*, Butterworth Architecture

Two excellent books on the 'parts of buildings' with clear drawings to complement the photographs

Keith Critchlow, *Order in Space*, Thames and Hudson

The book on three-dimensional geometry

Christopher Dean (Ed.), *Housing the Airship*, Architectural Association

James Dyson, *Against the Odds*

Orion Business Books

James Dyson's fascinating autobiography outlining his design and business tribulations from Royal College of Art days to the final production of the Dyson Cyclone vacuum cleaner

H Engel, *Structure Systems*, Penguin

Giunti Florence, *The Art of Invention*

Leonardo and Renaissance Engineers

J E Gordon, *Structures and Why Things Don't Fall Down*, Penguin

The New Science of Strong Materials, Penguin

The Science and Structure of Things, Scientific American Library

Three books that are essential reading for an understanding of general structures, with very little maths

Sembach Leuthäuser Gössel, *Twentieth Century Furniture Design*, Taschen

Probably the most comprehensive book on the subject

Erwin Heinle and Fritz Leonhardt, *Türme (Towers)* (in German), DVA

Wide coverage of towers worldwide through the ages

Monica Henning-Schefold, *Transparenz und Masse*, Du Mont

A German book illustrating glazed malls and halls from 1800 to 1880 – masses of photographs

John Hix, *The Glass House*, Phaidon

A review of glass architecture up to the present

Alan Holgate, *The Work of Jorg Schlaich and his Team*,

Edition Axel Menges

A comprehensive and beautifully produced book on the work of the German engineer who to my mind is one of the great inspirational engineers of the twentieth century and who, together with his team, is still working today

Institution of Structural Engineers, *Structural Use of Glass in Buildings*

Probably the best technical design guide to structural glass and glazing including many design examples

Ross King, *Brunelleschi's Dome*, Chatto & Windus

The story of the construction of the Great Cathedral in Florence (completed in 1436)

Fritz Leonhardt, *Brücken (Bridges)*, Architectural Press

The comprehensive coverage of bridges worldwide through the ages

Angus J MacDonald, *Structure and Architecture*, Butterworth Architecture

This could be considered to be the companion volume to *Tony Hunt's Structures Notebook*

Rowland Mainstone, *Developments in Structural Form*, 2nd Edition, Allen Lane

Probably the best and most comprehensive book on structures of all ages with marvellous photographic coverage

Z Makowski, *Steel Space Structures*, Michael Joseph
A very good review of built structures with excellent photographs and diagrams

Robert W Marks, *The Dymaxion World of Buckminster Fuller*, Reinhold

The best of Bucky Fuller's ideas

Meadmore, *The Modern Chair*, Studio Vista

A good, but not very comprehensive review of modern chairs with scale drawings

John and Marilyn Newhart and Ray Eames, *Eames Design*, Ernst & John

A complete record of the multi-faceted work of Charles and Ray Eames

Frei Otto, *Tension Structures*, Volumes I and 2, MIT Press

These and other later books cover nets, membranes and pneumatics and see also the IL series

Martin Pearce and Richard Jobson, *Bridge Builders*, Wiley-Academy

Recent book on bridges again with superb photographs and illustrations, some overlap with Matthew Wells' book and with a briefer text

Jean Prouvé, *Prefabrication: Structures and Elements*, Pall Mall Press

Prouvé was a much underrated designer whose inventive work in the field of lightweight panels and structures has never been bettered although much of it was carried out fifty years ago

Peter Rice, *An Engineer Imagines*, Artemis

The engineering and philosophical memoirs of the famous engineer who sadly died much too young. A number of the seminal structures of the twentieth century are here including the Sydney Opera House, the Centre Pompidou, the Lloyds Building and many others.

Llyall Sutherland, *Master of Structure: Engineering Today's Innovative Buildings*

Publ. Lawrence King.

This is the book that gives credit to the usually unacknowledged work of the engineer. It clearly shows the collaboration between engineer and architect that is essential to produce a good building

Robert le Ricolais, *Visions and Paradox*,
Fundacion Cultural C.O.A.M.

The inventor of the 'Hollow Rope' structural principle with drawings and illustrations of all his many experimental models

Salvadori and Heller, *Structure in Architecture*,
Prentice Hall

Salvadori and Levi, *Structural Design in Architecture*, Prentice Hall

Two very good books on building structures, the first entirely non-mathematical, the second with worked examples

Daniel Schodek, *Structures*, Prentice Hall

A good comprehensive textbook on basic principles with analysis and design

Dennis Sharp (Ed.), *Santiago Calatrava*, Book Art

Thomas Telford Press, *The Engineers Contribution to Contemporary Architecture*

Monographs by various authors on the following engineers: Eladio Dieste, Anthony Hunt, Heinz Isler, Peter Rice and Owen Williams. A self-explanatory series of books reflecting the title, with more volumes to come

Eduardo Torroja, *Philosophy of Structures*,
University of California Press

Maritz Vandenburg, *Soft Canopies*, Academy Editions

A good primer on tensile membrane structures

Maritz Vandenburg, *Glass Canopies and Cable Nets*, Academy Editions

Two good primers on the subjects with beautiful drawings.

Konrad Wachsmann, *Turning Point in Building*,
Reinhold

A seminal book on jointing and ideas on long span structures

Matthew Wells, *30 Bridges*, Lawrence King

A book discussing the history of bridge building and giving examples together with superb sketches and photographs of 30 interesting bridges with analysis of their behaviour

Michael White, *Isaac Newton the Last Sorcerer*,
4th Estate

A fascinating biography of a brilliant but not entirely likeable genius

Chris Wilkinson, *Supersheds*, 2nd Edition,
Butterworth Architecture

The definitive work on clear span structures from the nineteenth century to the present